AD-780 062

AGARD FLIGHT TEST INSTRUMENTATION SERIES. VOLUME 1. BASIC PRINCIPLES OF FLIGHT TEST INSTRUMENTATION ENGINEERING

A. Pool, et al

Advisory Group for Aerospace Research and Development
Paris, France

1973

DISTRIBUTED BY:

NTIS
National Technical Information Service
U. S. DEPARTMENT OF COMMERCE
5285 Port Royal Road, Springfield Va. 22151

AGARD-AG-160
Volume 1

NORTH ATLANTIC TREATY ORGANIZATION

ADVISORY GROUP FOR AEROSPACE RESEARCH AND DEVELOPMENT

(ORGANISATION DU TRAITE DE L'ATLANTIQUE NORD)

AD780062

AGARDograph No.160 Vol.1

BASIC PRINCIPLES OF FLIGHT TEST INSTRUMENTATION ENGINEERING

Edited by

A.Pool and D.Bosman

Volume 1

of the

AGARD FLIGHT TEST INSTRUMENTATION SERIES

Edited by

W.D.Mace and A.Pool

DDC
RECEIVED
JUN 17 1974
D

Reproduced by
NATIONAL TECHNICAL
INFORMATION SERVICE
U S Department of Commerce
Springfield VA 22151

This AGARDograph has been sponsored by the Flight Mechanics Panel of AGARD.

DISTRIBUTION STATEMENT A
Approved for public release;
Distribution Unlimited

THE MISSION OF AGARD

The mission of AGARD is to bring together the leading personalities of the NATO nations in the fields of science and technology relating to aerospace for the following purposes:

- Exchanging of scientific and technical information;
- Continuously stimulating advances in the aerospace sciences relevant to strengthening the common defence posture;
- Improving the co-operation among member nations in aerospace research and development;
- Providing scientific and technical advice and assistance to the North Atlantic Military Committee in the field of aerospace research and development;
- Rendering scientific and technical assistance, as requested, to other NATO bodies and to member nations in connection with research and development problems in the aerospace field;
- Providing assistance to member nations for the purpose of increasing their scientific and technical potential;
- Recommending effective ways for the member nations to use their research and development capabilities for the common benefit of the NATO community.

The highest authority within AGARD is the National Delegates Board consisting of officially appointed senior representatives from each member nation. The mission of AGARD is carried out through the Panels which are composed of experts appointed by the National Delegates, the Consultant and Exchange Program and the Aerospace Applications Studies Program. The results of AGARD work are reported to the member nations and the NATO Authorities through the AGARD series of publications of which this is one.

Participation in AGARD activities is by invitation only and is normally limited to citizens of the NATO nations.

The content of this publication has been reproduced
directly from material supplied by AGARD or the authors.

Published April 1974

681.2.087:533.6.054:629.73.058

Printed by Technical Editing and Reproduction Ltd
Harford House, 7–9 Charlotte St, London. W1P 1HD

PREFACE

Soon after its foundation in 1952, the Advisory Group for Aeronautical Research and Development recognized the need for a comprehensive publication on flight test techniques and the associated instrumentation. Under the direction of the AGARD Flight Test Panel (now the Flight Mechanics Panel), a Flight Test Manual was published in the years 1954 to 1956. The Manual was divided into four volumes: I. Performance, II. Stability and Control, III. Instrumentation Catalog, and IV. Instrumentation Systems.

Since then flight test instrumentation has developed rapidly in a broad field of sophisticated techniques. In view of this development the flight Test Instrumentation Committee of the Flight Mechanics Panel was asked in 1968 to update Volumes III and IV of the Flight Test Manual. Upon the advice of the Committee, the Panel decided that Volume III would not be continued and that Volume IV would be replaced by a series of separately published monographs on selected subjects of flight test instrumentation: the AGARD Flight Test Instrumentation Series. The first volume of this Series gives a general introduction to the basic principles of flight test instrumentation engineering and is composed from contributions by several specialized authors. Each of the other volumes provides a more detailed treatise by a specialist on a selected instrumentation subject. Mr W.D.Mace and Mr A.Pool were willing to accept the responsibility of editing the Series, and Prof. D.Bosman assisted them in editing the introductory volume. AGARD was fortunate in finding competent editors and authors willing to contribute their knowledge and to spend considerable time in the preparation of this Series.

It is hoped that this Series will satisfy the existing need for specialized documentation in the field of flight test instrumentation and as such may promote a better understanding between the flight test engineer and the instrumentation and data processing specialists. Such understanding is essential for the efficient design and execution of flight test programs.

The efforts of the Flight Test Instrumentation Committee members and the assistance of the Flight Mechanics Panel in the preparation of this Series are greatly appreciated.

T. VAN OOSTEROM
Member of the Flight Mechanics Panel
Chairman of the Flight Test
Instrumentation Committee

FOREWORD

to the first volume of the AGARD Flight Test Instrumentation Series

Only a few decades ago the main source of flight test information was the subjective judgment of the test pilot. As the complexity of the aircraft increased and as more methods for detailed analysis during the design phase became available, the need arose for more objective information. This led to the use of increasingly complex data collection systems in the aircraft and to the use of large data processing centres in which the measured data are converted to a form in which they can be directly interpreted. The industry produces a large variety of transducers and electronic components which have been specially designed for flight test applications. Engineers specialized in instrumentation, electronics and data processing play an important part in the design and the execution of the flight tests. The flight test engineers, who have the overall responsibility for conducting the flight tests, have to co-ordinate the work of all these specialists, who often have a theoretical and practical background quite different from their own.

The main purpose of the AGARD FLIGHT TEST INSTRUMENTATION SERIES is to provide monographs on the more important aspects of flight test instrumentation as a reference for the flight test engineer. The first monographs in the series discuss in-flight temperature measurements, fuel flow and engine rotation speed measurements, open and closed-loop accelerometers and magnetic tape recording; they will be followed by others. In this introductory volume it has been tried to highlight the main lines along which a flight test instrumentation system is developed, to indicate the main steps which must be taken during the design and to define the basic concepts used by each specialist. Although the volume is mainly directed towards the flight test engineer and tries to provide him with knowledge about the disciplines of the instrumentation engineer, it is hoped that the other specialists involved in flight testing will also find useful information in it.

In this book a flight test system is considered to include both the data collection and the data processing systems. In order to obtain an optimal data flow, the overall designs of these two subsystems must be carefully matched; the detail development and the operation can then be done by separate groups of specialists. If a new data collection system has to be designed for use with an existing data processing system, the characteristics of the latter will have an important impact on the design of the former and it may well be necessary to modify the existing system if an optimal solution is to be obtained.

The main emphasis will be on the large automated instrumentation systems used for the initial flight testing of modern military and civil aircraft. This is done because there many of the problems, which are discussed here, are more critical. It does not imply, however, that smaller systems with manual data processing are no longer used. In general, the systems should be designed to provide the required results at the lowest possible cost. For many tests which require only a few parameters, relatively simple systems are justified, especially if no complex equipment is available to the user. Although many of the aspects discussed in this volume apply to both small and large systems, aspects of the smaller systems are mentioned only when they are of special interest.

The volume has been divided into three main parts. Part I defines the main starting points for the design of a flight test instrumentation system, as seen from the points of view of the flight test engineer and the instrumentation engineer. In Part II the discussion is concentrated on those aspects which apply to each individual measuring channel and in Part III the main emphasis is on the integration of the individual data channels into one data collection system and on those aspects of the data processing which apply to the complete system. The contents of these three parts will be briefly summarized below.

Part I, General considerations about the design of a flight test instrumentation system

In Chapter 1 a flight test engineer discusses the requirements of the system from the users' point of view. He mentions the different types of flight tests which occur and indicates the special requirements for each of these. In Chapter 2 an instrumentation engineer describes how the design of an instrumentation system should be organized and mentions the most important aspects which determine the basic design of the system.

Part II, Design of a single measuring channel

Chapter 3 gives a short introduction into measurement theory and defines and describes such concepts as error, accuracy, dynamic response, etc. Chapter 4 reviews the characteristics of transducers, which generate the (electrical) signals from which the measurements are generally derived. The emphasis in this

chapter is on the transducer output characteristics, which mainly determine the requirements for the circuits to which they will be connected. In Chapter 5 the main signal conditioning circuits are reviewed. These are the circuits which are used to adapt the transducer output signals to the input requirements of the recorder or telemetry transmitter. One important aspect of signal conditioning, the filtering required for the accurate reconstruction of a continuous signal from sampled data, is discussed separately in Chapter 6. Part II ends with a discussion of calibration in Chapter 7.

Part III, Design of multi-channel instrumentation systems

Chapter 8 reviews the general design aspects of multi-channel data collection systems. Chapter 9 gives a short discussion of the characteristics of the different types of recorders and recording methods which are used in flight testing. Chapter 10 reviews the methods of telemetry. The special aspects of ground-based measurement equipment such as radar and kinetheodolites are mentioned in Chapter 11, together with the methods for synchronization of these measurement systems with on-board recorders. The final chapter is devoted to the general design aspects of data processing systems.

To conclude this foreword, something should be said about the way in which this book was compiled. The editors had been asked to prepare a comprehensive book covering the whole subject, not a collection of papers which would show many duplications and in which some subjects might have been treated too briefly or not at all. Though all authors co-operated with great enthusiasm, it was found that the fact that they were scattered over five countries prevented detailed deliberation about the details of the partition of the subjects over the different chapters. The editors therefore found it necessary to rearrange some of the chapters and to move sections from one chapter to another. The editors would like to express their deep gratitude to the authors both for the excellent work they did when writing their original draft chapters and for their friendly co-operation in the rearrangements necessary for the final book. The editors are also very thankful for all the advice and encouragement which they received from the members of the Flight Test Instrumentation Committee of the Flight Mechanics Panel of AGARD.

Amsterdam, December 1973

A. Pool
D. Bosman

Acknowledgement

The editors are very much indebted to the Directors of the National Aerospace Laboratory NLR, Amsterdam, for their substantial support to the preparation of this volume, and to several staff members of NLR who generously contributed a considerable part of their spare time to the editing process. In particular, they express their appreciation for the assistance of Mr. J.C. van der Linden, who conscientiously reviewed the text and prepared the index, and of Mrs. M.Brons, who took care of all administrative work and of the correction of the text. Special thanks are also due to Miss J.D. Bouter and Miss M.L. Lodewijk, who were responsible for the typing, and to Mr. J.T.A.M. Groos, who prepared the figures.

CONTRIBUTORS TO THIS VOLUME

Authors

A. Becker, Deutsche Forschungs- und Versuchsanstalt für Luft- und Raumfahrt DFVLR, Braunschweig, Germany

J.T.M. van Doorn, National Aerospace Laboratory NLR, Amsterdam, The Netherlands

B.L. Dove, NASA Langley Research Center, Hampton Va, USA

L.W. Gardenhire, Radiation Inc., Melbourne Fa, USA

M.L. Henney, British Aircraft Corp., Preston, United Kingdom

J. Idrac, Centre d'Essais en Vol, Brétigny, France

W.G. James, Flight Dynamics and Control Laboratory, Dayton, Ohio, USA

J. Perrochon, Centre d'Essais en Vol, Brétigny, France

C. Roquefeuil, Société de Fabrication d'Instruments de Mesure SFIM, Massy, France

H.L. Tollisen, The Boeing Company, Seattle, Wash., USA

D.A. Tougas, The Boeing Company, Seattle, Wash., USA

R.L. van der Velde, National Aerospace Laboratory NLR, Amsterdam, The Netherlands

O. Weber, Deutsche Forschungs- und Versuchsanstalt für Luft- und Raumfahrt DFVLR, Braunschweig, Germany

L.H. Weirather, NASA Flight Research Center, Edwards AFB, Cal, USA

Editors

D. Bosman, Technical University, Enschede, The Netherlands

A. Pool, National Aerospace Laboratory NLR, Amsterdam, The Netherlands

CONTENTS

	Page
FOREWORD	iv
CONTRIBUTORS TO THIS VOLUME	vi
Part I, General considerations about the design of a flight test instrumentation system	
1 The users' requirements, by M.L. Henney	
1.1 Introduction	1.1
1.2 The flight test process - general requirements	1.1
1.2.1 Overall trials planning	1.1
1.2.2 The quick-look analysis	1.2
1.2.3 Full data analysis and reporting	1.3
1.2.4 Required accuracy	1.3
1.3 The requirements of specific types of testing	1.5
1.3.1 Uncertificated aircraft	1.5
1.3.1.1 Development trials	1.5
1.3.1.2 Experimental aircraft	1.7
1.3.2 Certificated aircraft	1.7
1.4 Data analysis requirements	1.8
1.5 Summary and conclusions	1.8
1.6 References	1.9
2 An introduction into the design of flight test instrumentation systems, by B.L. Dove	
2.1 Introduction	2.1
2.2 Factors influencing instrumentation system design	2.1
2.2.1 Introductory remarks	2.1
2.2.2 The measurements list	2.3
2.2.3 The overall design of the instrumentation system	2.3
2.2.4 Other factors of influence on system design	2.6
2.3 Conclusion	2.8
2.4 References	2.9
Part II, Design of a single measuring channel	
3 Metrological characteristics of a measuring channel, by J. Idrac	
3.1 Introduction	3.1
3.2 Phases in a measuring operation	3.1
3.3 Errors in a measurement	3.2
3.4 Measuring range	3.4
3.5 Sensitivity and linearity	3.4
3.6 Accuracy	3.5
3.7 Static accuracy	3.6
3.8 Dynamic accuracy	3.7
3.9 Finesse	3.10
3.10 References	3.11

	Page
4 Transducers, by L.H. Weirather	
4.1 Introduction	4.1
4.2 Characteristics of transducers	4.1
4.2.1 Introductory remarks	4.1
4.2.2 Input characteristics	4.1
4.2.3 Transfer characterisitcs	4.2
4.2.4 Output characteristics	4.3
4.3 Types of transducers	4.4
4.3.1 Active analog transducers	4.6
4.3.2 Passive analog transducers	4.7
4.3.2.1 Variable resistance transducers	4.7
4.3.2.2 Variable capacitance transducers	4.9
4.3.2.3 Variable inductance transducers	4.9
4.3.2.4 Variable differential transformers	4.10
4.3.2.5 Synchros	4.10
4.3.3 Pulse and frequency generating transducers	4.11
4.3.3.1 Pulse-generating transducers	4.11
4.3.3.2 Frequency-generating transducers	4.12
4.3.4 Digital transducers	4.12
4.3.5 Closed-loop transducers	4.13
4.4 References	4.14
5 Signal conditioning, by W.G. James	
5.1 Introduction	5.1
5.2 Linear operations on signals	5.2
5.2.1 Theoretical introduction	5.2
5.2.2 Amplification and attenuation	5.3
5.2.3 Filtering	5.6
5.2.4 Zero shifting	5.8
5.2.5 Compensation	5.8
5.3 Signal conversion	5.9
5.3.1 General aspects	5.9
5.3.2 Modulation	5.9
5.3.3 Demodulation	5.11
5.3.4 Commutation	5.12
5.3.5 Analog-to-digital conversion	5.13
5.4 Conclusion	5.15
5.5 References	5.15
6 Sampling and filtering, by L.W. Gardenhire	
6.1 Introduction	6.1
6.2 Aliasing errors or errors of commission	6.1
6.3 Pre-sampling filters	6.3
6.4 Interpolation	6.5
6.5 Interpolation errors	6.6
6.6 A few practical observations	6.11
6.7 Conclusions	6.12
6.8 References	6.13

Page

7 Calibration, by D.A. Tougas
7.1 Introduction 7.1
7.2 The scope of calibration 7.1
7.2.1 Complete calibrations 7.1
7.2.2 Limited calibrations 7.2
7.3 Standards 7.3
7.4 Static calibration 7.3
7.5 Dynamic calibration 7.6
7.6 Calibration of environmental parameters 7.7
7.7 The overall calibration of a measuring channel 7.8
7.8 References 7.9

Part III, Design of multi-channel instrumentation systems

8 Technical aspects in the design of multi-channel data collection systems, by H.L. Tollisen and R.L. van der Velde
8.1 Introduction 8.1
8.2 System concept 8.2
8.2.1 System modification versus new development 8.2
8.2.2 Choice of the major components 8.2
8.2.3 On-board recording and/or telemetry 8.3
8.2.4 Methods of on-board recording and telemetry 8.4
8.2.5 Data processing aspects in the design of a data collection system 8.6
8.3 Technical design and development considerations 8.7
8.3.1 Introduction 8.7
8.3.2 Commutation and normalization of input signals 8.7
8.3.3 Maintenance and performance monitoring of the data collection system 8.10
8.3.4 System integration 8.11
8.3.4.1 Integration of main components into a complete system 8.11
8.3.4.2 Integration into the aircraft 8.12
8.3.5 Grounding 8.13
8.3.6 Electrical power 8.14
8.3.7 Data analysis requirements of the instrumentation engineer 8.14
8.4 The testing of instrumentation systems 8.15
8.4.1 Environmental testing 8.15
8.4.2 Functional testing 8.16
8.4.3 Total system check-out in the aircraft 8.16
8.4.4 Preflight and postflight checks 8.17
8.5 References 8.18

9 On-board recording, by C. Roquefeuil
9.1 Introduction 9.1
9.2 Photo-panel recording 9.1
9.2.1 General aspects 9.1
9.2.2 Advantages 9.1
9.2.3 Disadvantages 9.2
9.2.4 Range of applications 9.2
9.2.5 Typical installations 9.2

Page

9.3 Continuous-trace recording 9.2
9.3.1 General aspects 9.2
9.3.2 Advantages of continuous-trace recording 9.3
9.3.3 Disadvantages of continuous-trace recording 9.3
9.3.4 Range of applications 9.3
9.3.5 Typical data, pen recorders 9.4
9.3.6 Typical data, photographic recorders 9.4
9.4 Analog magnetic tape recording 9.5
9.4.1 General aspects 9.5
9.4.2 Advantages of analog tape recording 9.6
9.4.3 Disadvantages of analog tape recording 9.7
9.4.4 Range of applications 9.7
9.4.5 Typical data on analog tape recording systems 9.7
9.5 Digital magnetic tape recording 9.9
9.5.1 General aspects 9.9
9.5.2 Advantages of digital tape recording 9.11
9.5.3 Disadvantages of digital tape recording 9.11
9.5.4 Range of applications 9.11
9.5.5 Typical data on digital tape recording systems 9.11
9.6 Conclusion 9.12
9.7 References 9.12

10 Telemetry, by A. Becker
10.1 Introduction 10.1
10.2 Modulation and multiplexing 10.2
10.2.1 Description of the basic methods 10.2
10.2.2 Modulation and multiplexing used in telemetry systems 10.6
10.3 The radio frequency link 10.7
10.4 Chronographic recording and display 10.9
10.5 Comparison of IRIG-standardized telemetry systems 10.10
10.6 On-line data processing 10.12
10.7 References 10.12

11 Ground-based equipment, by O. Weber
11.1 Introduction 11.1
11.2 Capabilities of a trajectory measuring system 11.1
11.2.1 Co-ordinate systems 11.1
11.2.2 Determination of the velocity vector 11.2
11.3 Selection of the trajectory measuring system 11.2
11.3.1 Kinetheodolites 11.2
11.3.2 Tracking radar 11.3
11.4 Optimal position of the trajectory 11.4
11.5 Take-off and landing measurements 11.5
11.6 Time and time standards 11.6
11.7 Synchronization of trajectory measuring systems 11.7
11.8 Synchronization of ground-based and airborne measuring equipment 11.7
11.8.1 Exact synchronization by technical means 11.8
11.8.2 Synchronization by interpolation 11.9
11.9 References 11.10

	Page
12 Data processing, by J. Perrochon and J.T.M. van Doorn	
12.1 Introduction	12.1
12.2 Functional analysis of data processing	12.1
12.2.1 General aspects	12.1
12.2.2 Types of data input	12.2
12.2.3 Quick look and instrumentation checking	12.3
12.2.4 Preprocessing	12.3
12.2.5 Computation	12.6
12.2.6 Presentation	12.7
12.2.7 Validation and interpretation	12.7
12.3 Short description of a few processing techniques	12.7
12.3.1 Application of calibrations	12.7
12.3.2 Smooting and filtering	12.10
12.3.3 Time correlation	12.10
12.4 Short discussion of data processing equipment	12.11
12.4.1 Equipment for analyzing photo-panel recordings and continuous-trace recordings	12.11
12.4.2 Equipment for quick look and instrumentation checking	12.11
12.4.3 Preprocessing equipment for magnetic tape inputs	12.11
12.4.4 Computers	12.12
12.5 Concluding remarks	12.13
12.6 References	12.14
INDEX	

PART I

GENERAL CONSIDERATIONS ABOUT THE DESIGN OF A FLIGHT TEST INSTRUMENTATION SYSTEM

CHAPTER 1

THE USERS' REQUIREMENTS

by

M.L. Henney

1.1 INTRODUCTION

A test is defined in the dictionary as "a trial determining a thing's quality or fitness for a purpose" involving "critical examination". Flight testing is the subjecting of airborne vehicles and their equipment to such trials, and flight test instrumentation is the means whereby behaviour under test is measured and recorded for subsequent analysis.

Flight tests are conducted for a variety of reasons but the aircraft involved fall into two categories:

(a) Uncertificated aircraft

(i) New or modified vehicles requiring operational clearance (certification).

(ii) Experimental aircraft intended solely for specific research objectives.

(b) Certificated aircraft

(i) In-service trials on military and civil aircraft, involving operational studies, tactical trials, weapon system optimization, etc.

(ii) Investigation of post certification deficiencies.

(iii) Development of new airborne and ground systems and equipment in which a "flying platform" is involved; "flying test beds" (engines), "flying laboratories".

(iv) Research and teaching.

Whereas these various types of testing place many common requirements on the instrumentation systems, special requirements also arise in each case, and these will be examined in this chapter from the point of view of the user.

We shall deal with the instrumentation system in its widest sense, comprising both the airborne and ground equipment and the people involved in gathering the necessary data and presenting it to the users in the required form. The users include design engineers and operations specialists.

An important specialist activity that has gained prominence in recent years is the automation of the analysis of data recorded on magnetic tape. Data processing and analysis engineers have developed systems and methods for such automation. It should be kept in mind, however, that a detailed knowledge beforehand of the characteristics of the input signal (especially the frequency spectrum, including noise) is even more essential for these automated systems than for manual data processing. An incorrect assumption on these signal characteristics may cause large errors (for instance by aliasing, see Chapter 6), which often cannot be detected from the final data output. The users must be fully aware of the details of the processing that has been performed, in order that any limitations of the methods are fully understood and that erroneous conclusions from test results are avoided.

In Section 1.2 the manner in which general requirements on the instrumentation system are derived, are indicated by considering the test planning process and data analysis. In Section 1.3 specific requirements arising in various categories of tests are detailed, and in Section 1.4 further elaboration of the data analysis requirements are given.

1.2 THE FLIGHT TEST PROCESS - GENERAL REQUIREMENTS

1.2.1 Overall trials planning

The requirements for the instrumentation system must be determined by a careful and systematic examination of the aircraft and its systems in the flight test planning phase to determine the tasks to be performed. Answers to the following questions should be provided for each task:

(a) What is the overall objective?

(b) What trials best satisfy the objective?

(c) What parameters should be measured? Is external instrumentation, such as kinetheodolites, photography, also required?

(d) What range, frequency and accuracy is required for each parameter?

(e) What processing is required on the data? What form of presentation is needed? What requirements exist for data storage and retrieval?

(f) What analysis is required? Is accurate time correlation of the various internal and external recorders required?

(g) What data turn-round time is required? Is on-line presentation and analysis needed?

(h) What special requirements exist, e.g. crash recording, on-line safety monitoring, etc? What special instruments are required for supporting qualitative assessments by the pilots, e.g. cameras for photographic tufts, ice formations, etc?

Subsequent integration of these tasks into an overall aircraft test plan will determine:

(j) How the total flight test programme will be divided between the different aircraft taking part in it. What parameters must be measured simultaneously in each of the aircraft.

(k) What additional instrumentation must be provided in order to make each aircraft capable of supporting and backing up the others in the event of major development problems, loss of an aircraft or other unforeseen events.

(l) What trials must be performed away from the main base.

(m) What opportunities there will be to re-instrument the aircraft or whether all necessary instrumentation equipment need to be installed from the start.

Finally, it is necessary to know:

(n) What space can be allocated to instrumentation equipment. What operational equipment can be displaced, if necessary.

(o) What other physical limits and requirements may apply, e.g. weight, power requirements, environmental conditions, etc.

The answers to these questions will permit the important characteristics of the airborne and ground equipments to be defined - required recording capacity and facilities, speed and scope of processing - and should permit the economics of possible solutions to be examined in detail.

The correct choice of instrumentation system has important effects on the efficiency of the flight test process. This will be examined further in Section 1.3 for the various types of flight trials.

In all trials, however, there are further general instrumentation system requirements which arise when the process of flight test data analysis is examined.

In Reference 1 the flight test process is examined in detail, and it is shown that in the analysis process two main stages are apparent; "quick look" and "full analysis and reporting". These are examined in turn.

1.2.2 The quick-look analysis

This has the objectives:

(i) To verify the correct functioning of the instrumentation equipment.

(ii) To establish that the required tests have been satisfactorily performed and adequate data is available for analysis.

(iii) To monitor the overall behaviour of the system under test and to ensure that there are no consistent anomalies which would indicate operational or safety hazards.

(iv) To permit early examination and diagnosis of unexpected development or engineering problems.

(v) To permit analysis requirements to be defined in detail.

Items (i) to (iv) are the direct concern of the flight test engineer and must be completed and actioned before the next flight may proceed, and must therefore be completed well within the planned turn-round time of the aircraft. This will permit any necessary repeat testing, or alternate test scheduling as a result of the findings, to be included in the programme.

Quick-look stages (i), (ii) and (iii) may be performed "on-line", i.e. whilst the aircraft is actually flying, either by the airborne test crew (in the case of large aircraft) or through use of telemetry to permit on-line display to engineers on the ground. In these cases airborne testing time can be used much more efficiently by allowing immediate repeats of tests if necessary or by changing to alternative programmes if instrumentation unserviceability or other operational factors (systems malfunction, weather, etc.) require it. The use of such systems will also permit stages (iv) and (v) and subsequent analysis to be begun earlier.

If the programme size or the risk is not sufficient to economically justity the use of telemetry or an on-board quick-look system, then postflight quick look must satisfy these needs.

Item (iv), the investigation of unexpected occurences, requires a high degree of flexibility in the instrumentation system. The instrumentation system must be able to capture the events (including transients) without undue distortion. Continuous recording devices (e.g. trace recorders) have such flexibility, subject only to the frequency response of the channel and to limitations in resolution due to the chosen paper speed. Sampling devices can be more accurate for low-frequency inputs but define data poorly at frequencies near the "Nyquist frequency" and can be completely misleading if higher frequencies occur. This latter problem can only be overcome whilst retaining high recording capacity if some form of adaptive sampling is adopted (Ref. 2), or alternatively, if the sampled system installed for performance testing is supplemented by some less accurate continuous recording system for capturing transient incidents. Further, to ensure the capturing of any unexpected incident, it would be necessary that the instrumentation system was recording a sufficiently comprehensive selection of parameters throughout every flight. If this were not possible, or if sampling rate were not adequate, then it would be necessary to hazard the aircraft by trying to repeat the incident using appropriate instrumentation.

The use of a high-capacity instrumentation system can thus reduce the risk involved in test flying.

1.2.3 Full data analysis and reporting

Data analysis has the objectives:

(i) To further ensure the safe and satisfactory progress of the test, and

(ii) To yield the information necessary to satisfy the ultimate objectives of the users:

(a) Aircraft and systems performance.

(b) Safe operational limits.

(c) Safe operation life.

(d) Proof of compliance with requirements, etc.

The first of these objectives is particularly relevant to development trials in which safe progressive clearance depends on the extrapolation of results from all previous tests to ensure that adequate margins of safety should exist in the next planned test (as in flutter testing for example).

If trials progress is not to be impeded then analysis must be performed quickly (within the planned turn-round of the aircraft) or the aircraft should be equipped to perform some alternative independent trial while the results are processed.

In general, analysis involves large numbers of routine calculations with subsequent collation, manipulation and interpretation of results from a test series. Calculation, collation and manipulation are processes which are ideally suited to the programmable capability of general purpose digital and analogue computing equipment, and rapid analysis requires that the necessary data is recorded in a form which can be readily fed into such computing systems. However, the state of the art is such that analyst intervention and guidance is often necessary, and such facilities should be recognised and provided in the processing system.

In certain circumstances "semi on-line" analysis may be justified to allow satisfactory progress in areas of high risk testing. This is a process where use of telemetry allows capture of test data which is then quickly analysed whilst the aircraft continues flying, so that decisions whether or not to proceed may be taken by highly qualified specialists on the ground using these test results.

1.2.4 Required accuracy

The required accuracy of the instrumentation system and the individual parameters are determined by reference to their contribution to the overall error in the final results. To take a simple example let us assume we are required to measure the cruise performance of a simple turbo-jet powered aircraft. This can be done by establishing measurements to determine the stabilized values of weight (W), true airspeed (V) and fuel flow rate (F). It may well be required to hold flight conditions for 20 or 30 minutes to ensure adequately stabilized results. It is well known that the performance of this type of aircraft can be expressed in non-dimensional form using the parameter "specific air range" $\frac{WV}{F}$ which

is a function of Mach number (M) and weight function (W/δ) only (δ is the ratio of atmospheric static pressure relative to the standard sea level value), as indicated in Figure 1.1.

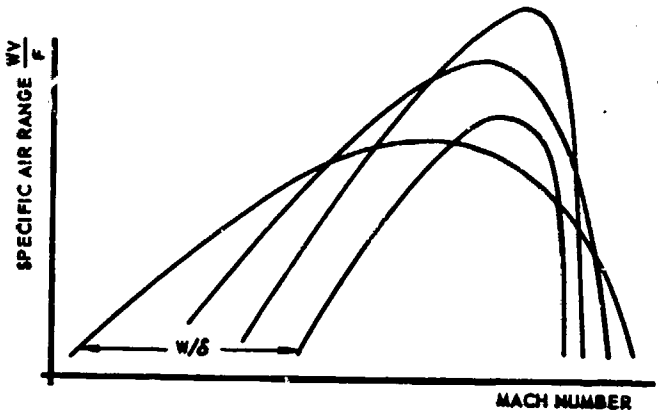


Figure 1.1 Typical graph showing specific air range $\frac{WV}{F}$ as a function of Mach number and W/δ

For these tests the following parameters would be measured:

atmospheric static pressure p
impact pressure q_c
total air temperature T_t
fuel weight remaining W_F
fuel flow rate F.

For the purpose of an example it will be assumed that the errors in these parameters are independent. This means that W_F is measured directly and not by integration of F and that the "position errors" on the first three parameters can be neglected. Then the equation of the relative error in the specific air range SR

$$\frac{dSR}{SR} = \frac{dV}{V} + \frac{dW}{W} - \frac{dF}{F}$$

can be expressed in the independent variables by using the relations

$$V = K.M.\sqrt{T}$$

$$\frac{p + q_c}{p} = (1 + 0.2\,M^2)^{3.5}$$

$$T_t = T(1 + 0.2\,M^2)$$

$$W = W_E + W_F$$

where K is a constant and W_E is the total weight of the aircraft without fuel. The error equation then becomes

$$\frac{dSR}{SR} = \frac{0.7}{M^2}\,\frac{q_c}{p + q_c}\left(\frac{dq_c}{q_c} - \frac{dp}{p}\right) + \frac{1}{2}\,\frac{dT_t}{T_t} + \frac{W_F}{W_E + W_F}\,\frac{dW_F}{W_F} - \frac{dF}{F}\,.$$

For the example we will assume that for each variable the standard deviation of the error is 1 % of the full range of measurement. The following table might represent a typical set of cruise values, measuring ranges and relative errors equivalent to a measuring error of 1 % of full scale.

	Cruise value	Full range of measurement	Relative error in the cruise value due to 1 % FS error	Relative error in specific range due to 1 % FS error
q_c	30,000 N/m^2	0 to 150,000 N/m^2	5 %	1.8 %
p	40,000 N/m^2	0 to 120,000 N/m^2	3 %	1.1 %
T_t	250 K	200 to 400 K	0.8 %	0,4 %
W_F	$\frac{1}{2}\,W_E$	0 to W_E	2 %	0.66 %
F	$\frac{1}{3}\,F_{max}$	0 to F_{max}	3 %	3.0 %

As will be seen the maximum fuel weight has been assumed to be half the total weight. The Mach number

is 0.93.

If one was unlucky and all the errors in the last column added up in the worst sense, then the error in the specific air range would amount to 7 %. It is, however, very unlikely that such a coincidence will occur if the variables are, as assumed here, statistically independent. If the values in the last column are regarded as standard deviations, the standard deviation of the error in the specific air range will be 3.6 %.

Such an error is too large to ignore and repeated measurements would be necessary to allow "true" performance to be implied as the average of the observations. (Note: this process will not eliminate the bias errors which might be expected when considering one set of equipment. However, careful calibration techniques (i.e. measuring and correcting for environmental factors) could go some way to eliminating these).

The above example has been chosen deliberately to illustrate how small errors in combination can become very significant, and indicates that demands of 1/4 % to 1/2 % full scale accuracy could easily be justified for this type of test. If non-steady test techniques are employed to reduce test time then it is found that better accuracy still will be required, 0.1 % full scale being desired, with better resolution to aid differentiation (see Ref. 1).

1.3 THE REQUIREMENTS OF SPECIFIC TYPES OF TESTING

The various classes of test aircraft were defined in the introduction, and the special requirements of each class will now be reviewed in turn.

1.3.1 Uncertificated aircraft

Safety is a primary consideration in all airborne operations and the normal operational instruments provide for this. In this class of aircraft, however, things are being done for the very first time. In consequence until the basic aircraft is proven, the special test instrumentation is involved in safety, and the need for rapid and accurate feedback of information from the instrumentation is of vital importance.

1.3.1.1 Development trials

The planning of such trials usually starts very early in the design process, and the instrumentation systems usually are installed during the construction of the aircraft.

Flight testing comprises a very significant part of the total development process of new aircraft types and much capital is tied up in it. The true prototype approach, in which sufficient development is completed to fully establish the design before production is committed, is often no longer viable and manufacture usually starts soon after development flying begins. There is therefore considerable commercial risk associated with the late discovery of development problems, involving both wastage of materials and effort, and the costs of late delivery to the customer. The reliability and accuracy of the data gathering system, and the speed and ease with which it enables the engineers to use the data, have a significant effect on the efficiency of the aircraft development process and therefore on the cost and profitability of the project. Flight trials planning should recognise this and the instrumentation systems should be chosen and designed accordingly.

Despite increasing complexity of aircraft and their systems, the elapsed time from first flight to certification is required to be kept constant or should even be reduced. This requires that flying rates are maintained or even increased and that test flying effectiveness is increased giving more useful data per test hour. As far as the instrumentation system is concerned this amounts to requirements for:

(a) High recording capacity, permitting integrated test programmes to be performed. For example, sufficient parameters need to be recorded to allow performance, stability and control, flutter and even systems tests to be undertaken at each of a number of test points on any given flight.
(b) High reliability and stability of calibration to minimise instrumentation work between flights.
(c) Telemetry may be used as indicated in Section 1.2.2 to increase testing efficiently and its use may also increase flight safety by permitting monitoring of systems behaviour and, when relevant, pilot actions (e.g. stalling and spinning tests).

Ideally, the flight test engineer requires an instrumentation and display system such that he can safely and quickly explore the whole operational flight envelope to identify major problems; subsequently concentrating on solving these problems and gathering all of the formal data necessary for certification.

Further the flight test and analysis engineers are required to develop techniques to obtain results of the required quality from less flying. Thus greater emphasis is being placed on the ability to extract information from non-steady tests. Hopefully no formal testing should ultimately be required to establish performance and stability and control data, this being extracted as a continuous process from all flying. This will require high accuracy from the instrumentation system, together with new analysis techniques. In the past, analysis of data has normally involved breaking down the observed behaviour into its parts by direct manipulation of the results. In this way the fundamental factors governing the behaviour can be revealed (for example, performance as a function of thrust, drag, and fuel consumption, each of which in turn can be expressed as functions of flight condition, aircraft configuration, engine conditions, etc.) but as test and aircraft complexity increase this becomes more and more difficult. In the writer's experience no satisfactory method of analysis has been developed to allow the completely automatic extraction of performance information from general non-steady manoeuvres, because of the difficulty in smoothing the data suitably. An alternative approach would involve synthesis, in which the expected behaviour under the actual conditions of test would be calculated from the relevant design data assumption and compared with actual behaviour. Satisfactory agreement may be taken as proof of design, or in the case of lack of agreement consistent amendments of the design assumptions would be made to obtain agreement.

Such techniques have already been applied with some success to aircraft performance testing and stability "matching" and could readily be extended to cover systems temperatures and performance, structural loading in manoeuvres etc. The technique lends itself to automation since in general the calculations are only special cases of design calculations.

Tests will be required in all aspects of:

- Stability and control
- Performance
- Structure (loads and flutter)
- Systems (including avionics)

and study of the special features of the aircraft along with the various applicable statutory requirements (Mil. Specs, FAA requirements, etc.) will determine the minimum basic test programme. However, many areas require very careful thought as to how best to perform tests and what measurements are necessary.

This is especially true in systems testing but it applies in other areas too. The proper use of ground rigs and simulators and mathematical modelling techniques generally will lead to minimum-cost solutions. This is best illustrated by examples:

(i) Alternator cooling trials

Alternators are ususally ram air cooled and two approaches to flight trials come to mind:

(a) Load the alternator electrically to its rated output - measure stabilised critical component temperatures (windings, brushes, etc.) at a number of points in the flight envelope (perhaps 30 minutes per point) - analyse the data to obtain the temperature-flight condition "law", and extrapolate to worst specification conditions and assess the adequacy. It may be necessary to perform tropical trials to confirm this prediction.

(b) Perform ground rig tests on a loaded alternator to determine minimum cooling air mass flow required over the expected cooling temperature range. The instrumentation intended for flight trials should be calibrated during these tests. Fly to measure the actual cooling air mass flow achieved in flight at the same test points as in (a), which should take only a few seconds per point, and confirm directly the adequacy of the measured mass flow. No extrapolation should be necessary and no tropical trials are needed for this reason.

It is seen that the second method will lead to considerable economy in flying time, and, since a suitable ground rig will probably exist for other reasons, will prove to be the more economic solution.

(ii) System testing

Here we are concerned with trials to establish the performance of the system under all possible circumstances (in this case performance involves important statistical variation, as for example in inertial navigation systems or weapon delivery systems, and we are required to predict the performance of the whole family of production aircraft and systems, and not just to state the performance of the few development systems that were tested).

If a model of the system can be established - this may be either a systems rig with "real world" simulation or an entirely theoretical model, for example a mathematical representation on a digital computer - then it can be used initially to aid trials planning. Subsequently, it can be used to help solve development problems and its performance can be "matched" to the observed behaviour in the flight trial. In this way the important characteristics of the system can be identified and fully represented. The performance to be expected from the production systems can be determined by inserting the expected characteristics (including tolerances) and large numbers of test runs can be simulated to establish statistics quickly and relatively cheaply.

Without the use of a model the solution of development problems may prove very difficult, and extensive flight trials would be required involving different sets of equipment in order to determine with confidence the representative statistics. This would be an extremely costly process.

When all of the requirements have been collected, careful thought should be given first to the use of existing company owned equipment and facilities to solve the problem. These will be well known, personnel will be already experienced in their use and any shortcomings can be easily recognised and corrected. Only if these facilities are not adequate, should attention first be directed to available off-the-shelf equipment and, as a last resort, to the building and development of completely new systems. In this latter case every effort should be made to develop and prove the chosen system using a suitable test vehicle, otherwise the development of the new aircraft will be slowed by the need for parallel development of the instrumentation systems.

1.3.1.2 Experimental aircraft

The emphasis here must be on obtaining minimum operational and safety clearance of the various essential systems followed by progressive penetration into the areas of flight dictated by the research objectives.

Parameter lists and analysis requirements are likely to contain new and novel requirements and the instrumentation of any special full scale rigs and gantries (of the type much in evidence in VTOL work) is an additional concern of the flight test engineer. The high temperatures and temperature transients occurring in aircraft used for research at very high speeds present many difficult problems in the design of the data collection systems.

There is likely to be an even greater emphasis on the need for telemetry safety monitoring if complex control systems are involved or if significantly new flight regimes are being explored, and this can also fulfill the requirement for accident data recording.

In most research programmes with experimental aircraft the flying rate is relatively low (e.g. one flight per week or less). The main reasons for this are that usually a detailed analysis of the flight data must be made before the next flight can be planned, and that flight with experimental aircraft require extensive ground preparations and preflight/postflight checks. Under these circumstances the turn-round time of the data processing equipment may still be the limiting factor in the preparation of each new flight, notwithstanding the low flying rate. For each programme this turn-round time should, therefore, be carefully planned. For some long-term research programmes the flying rate is mainly determined by the allowed rate of expenditure. In such cases the demand for rapid turn-round of instrumentation data is likely to reduce in favour of more systematic and thorough data analysis procedures.

1.3.2 Certificated aircraft

The type of instrumentation used in tests with certificated aircraft will depend very much on the type of test made. For the investigation of deficiencies of the aircraft or its equipment very simple systems with only a few channels can often be used. In some cases the AIDS system already available in the aircraft can be used after slight modification. For large-scale operational tests and for the

development of new equipment or new engines in "flying platforms" more complex data collection systems and automatic processing are often necessary. In such cases the equipment developed for the initial flight testing of the aircraft type can sometimes do very good service. For teaching it is likely that, to get at the fundamentals, the most simple and basic instrumentation systems are used so that the student may fully experience all stages in the flight testing process.

When instrumenting an operational aircraft very careful attention to detail will be required to avoid interference with systems operation and to maintain systems reliability. For these reasons it may be best to produce an entirely self-contained instrumentation package with independent transducers rather than to "tap into" normal aircraft systems. In some cases such self-contained systems are mounted in modified detachable fuel tanks, so that they can be used on all aircraft of the same type.

Development trials of systems and equipment are likely to be even more intensive than aircraft development trials, whereas trials involving operational transport aircraft are probably the least intensive, being secondary to revenue earning and involving long delays between conduct of a flight and return of the recording to some central processing and analysis facility (Ref. 3).

1.4 DATA ANALYSIS REQUIREMENTS

Efficient flight testing requires the rapid turn-round of fully analysed results in order to ensure recognition and reaction to development problems and/or the need to repeat testing with the minimum wastage of flying.

The formal analysis process can be speeded up considerably by the use of digital computers, especially if the data is recorded in a form permitting automatic input to such machinery. If such a system is adopted then a great deal of effort must be devoted to the development and proving of the necessary data handling and analysis programmes before flying commences. The computer programme should be flexible enough to enable changes to be introduced quickly.

However, to help speed up the solution of unforeseen development problems, requiring unscheduled analysis of the recorded data, the power and speed of the computing system must be capable of direct control by the user in an interactive way, so that data can be displayed, manipulated and operated upon progressively as new facts are discovered and clues are followed up.

Such a system should operate just as one would with slide rule and graph pad, but dividing the functions so that the engineer does the decision making and control and the machine does the arithmetic and presentation at very high speed. The machine's repertoire should include not only the standard operations of data extraction, calibration and display of time histories, but also the calculation of standard functions (Mach number, energy height, lift coefficient, centre of gravity), insertion of "slide rule type" calculations, data editing and correction, smoothing, curve fitting and cross plotting. At each or any stage hard copy should be available on demand.

Interactive graphic terminals exist which permit such working and notable applications to the flight testing are the systems described in References 4 and 5, the former describing a particularly well developed system.

The final product of analysis should be technical reports in which data from a test series are collated and reported. This work can be usefully aided by establishing in the data handling machinery "data banks" in which test results are stored progressively as they are produced and subsequently handled interactively as described above for individual test data.

1.5 SUMMARY AND CONCLUSIONS

Users of flight test instrumentation require data gathering and analysis systems which have the following characteristics:

(a) High data gathering capacity with the ability to accept any mixture of types of analogue and digital signals.

(b) High overall accuracy where necessary.

(c) Good reliability.

(d) Good maintainability.

(e) Good flexibility, to cope with new requirements and unforeseen occurrences.

(f) Facilities for crash recording and telemetry monitoring when necessary.

(g) Data storage in a form suitable for direct entry to data processing and analysis equipment, systems rigs and mathematical models.

(h) Powerful interactive data analysis facilities.

The correct choice of system can have profound effects on the efficiency of flight testing and, in consequence, on the overall cost and profitability of a new aircraft project.

The optimum solution should be sought for each project from careful study of the tasks and the associated data analysis requirements, and the capability of existing resources to meet these. Co-operation between the flight test engineer, the instrumentation engineer, and the data analyst should allow this optimum to be identified.

There appears to be no universal optimum. On the contrary, the instrumentation systems are likely to vary as widely as the types of aircraft and the types of test for which they are intended. In later chapters of this book the different instrumentation system approaches will be discussed in greater detail and their particular fields of application will be indicated.

1.6 REFERENCES

1. M.L. Henney — Flight test instrumentation - The user's requirements, AGARD Conference Proceedings no. 32 - Flight Test Instrumentation, 1967
2. R. Scheinman — Digital adaptive recording system, Proceedings of the 5th International Aerospace Symposium, Cranfield, March 1968
3. Civil aircraft airworthiness data recording programme (CAADRP), RAE Technical Report 64004, September 1964
4. R.M. Hutchins — Grumman Automated Telemetry System (ATS), Report No. C.A.F.T. 35, Symposium on Computer Automated Flight Testing, Society of Flight Test Engineers, October 1970
5. L.D. Crowley — Real time graphic flight test becomes reality, Douglas Paper 5901, 17th National Aerospace Instrumentation Symposium, May 1971

CHAPTER 2

AN INDUCTION INTO THE DESIGN OF FLIGHT TEST INSTRUMENTATION SYSTEMS

by

B.L. Dove

2.1 INTRODUCTION

Flight tests programs invariably represent a significant investment of resources, and therefore, considerable care must be devoted to identifying the specific requirements for the flight tests and to assure that the data system will yield the required information. The types of flight test information which can be obtained are discussed in Section 1.1 of this book. The first step towards the realisation of a flight test instrumentation system then is a clear statement of the objectives of the flight test program. These objectives are drawn up by the specialists which require the information: for instance, the office which has designed a new aircraft or a new piece of equipment which must be tested, or the operations office having a need to experiment with new military air tactics. On the basis of these objectives, the flight test organization will prepare a preliminary flight test program, a list of parameters which must be measured, and other special requirements, such as those mentioned in Section 1.2.1 of Chapter 1.

At this stage of the design process, various ways of organizing to accomplish the work are utilized, each with its own advantages. Should a project organization be created, an instrumentation systems engineer would normally be assigned to the organization along with flight test engineers and test pilots. Data processing specialists are rarely assigned to a specific project, but this decision depends upon the merits of each case.

The instrumentation design phase which follows begins when the flight test engineers develop a measurements list (see Section 2.2.2). Using this list, the instrumentation engineer produces an overall design approach for the instrumentation system.

In the instrumentation development phase, the hardware and software of the instrumentation system are developed by technical specialists. In this phase, commercially available parts will have to be chosen and ordered, and the parts of the system which must be made in-house are designed. At the end of this phase, the actual hardware and software have been produced.

When the total instrumentation system, or at least major parts of it are ready, they pass into the test phase. The importance of this phase is often underestimated, with the result that "teething troubles" sometimes cause delays in the transition to the operational phase of the flight test program. It is very important to take instrumentation testing requirements into account when planning a flight test program, for in some cases it has required as much time as the design and development phases together. Many of the tests can be done in the laboratory, but experience has shown that actual flight testing of the airborne equipment is essential as it reveals weak points which were not apparent during tests under simulated conditions. This phase can also be used to train equipment operators and maintenance personnel, and to finalise maintenance schedules.

The general procedure described above is generally applicable for the design of instrumentation systems used for testing modern high-performance aircraft.

2.2 FACTORS INFLUENCING INSTRUMENTATION SYSTEM DESIGN

2.2.1 Introductory remarks

The main task of the design project group is flight test program planning which includes finalisation of the measurements list, and, subsequently, the determination of the instrumentation system design approach.

The design selected for an instrumentation system is a reaction to requirements resulting from discussion of the long-range plans of the flight test program, and the specific details of the current flight test plans which include all topics discussed previously in Section 1.2.1.

In the normal cours of events, several avenues to program success exist for the flight test engineer. From an instrumentation point of view, some of the possible approaches to the flight test program may require much more complicated instrumentation systems than others. For this reason, flight

	Measurement Type	Location	Range	Resolution Percent Full-Scale	Accuracy Percent Full-Scale	Frequency Response Hertz	Priority	Remarks
1	Airspeed	Aft Equipment Bay	0-500 kts	0.1	±1	1 Hz	P	P = Primary; S = Secondary
2	Altitude	Aft Equipment Bay	0-40,000 ft	0.1	±1	1 Hz	P	
3	Angle-of-Attack	Nose Boom	+35°, -15°	0.1	±1	3 Hz	P	
4	Angle-of-Sideslip	Nose Boom	± 25°	0.1	±1	3 Hz	P	
5	Pitch Attitude	Aft Equipment Bay	± 85°	0.1	±1	3 Hz	P	Derived from
6	Roll Attitude	Aft Equipment Bay	± 180°	0.1	±1	3 Hz	P	Synchro Outputs
7	Yaw Attitude	Aft Equipment Bay	± 180°	0.1	±2	3 Hz	P	of Ship's Gyros
8	Piton Rate	Aft Equipment Bay	±100°/sec	0.1	±1	20 Hz	P	
9	Roll Rate	Aft Equipment Bay	±250°/sec	0.1	±1	20 Hz	P	
10	Yaw Rate	Aft Equipment Bay	±100°/sec	0.1	±1	20 Hz	P	
11	Normal Accelerometer	C.G. (in wing over engine)	+8g, -2g	0.1	±1	10 Hz	P	
12	Longitudinal Accelerometer	C.G. (in wing over engine)	±2g	0.1	±1	10 Hz	P	
13	Lateral Accelerometer	C.G. (in wing over engine)	±2g	0.1	±1	10 Hz	P	
14	Fuel Flow	Aft Equipment Bay	(Counter)	0.3	±0.3	—	P	
15	Altitude Rate	Aft Equipment Bay	±30,000 ft/min	0.1	±2	1 Hz	S	Differentiation of Altitude
16	Engine Inlet Temperature	Engine Inlet	0 ÷ 200°F	0.1	±2	3 Hz	S	
17	Aileron Position	Left Wing	±12.5°	0.1	±1	3 Hz	P	
18	Stabilizer Position	Aft Equipment Bay	+10°, -11°	0.1	±1	3 Hz	P	CPT's on Control
19	Rudder Position	Aft Equipment Bay	±15°	0.1	±1	3 Hz	P	Cables
20	Nozzle Position	Engine	0 ÷ 95°	—	±1	3 Hz	P	
21	Engine RPM	Aft Equipment Bay	0 ÷ 100 %	0.1	±1	1 Hz	P	
22	Exhaust Gas Temperature	Engine Tail Pipe	+500°C ÷ +700°C	0.1	±2	3 Hz	P	Determines Engine Life
23	Events	Aft Equipment Bay	(Counter)	—	—	—	S	
24	Time	Aft Equipment Bay	8 hours	1 msec	—	—	P	

Figure 2.1 Typical measurements list

test objectives must be specific and a discussion of them at an early stage must allow for an inquiry into the reasons behind their selection. Significant aspects can be, for instance, the division of the flight test program between a number of aircraft and the plans which exist for more or less similar flight tests with other types of aircraft.

2.2.2 The measurements list

Definition. A measurements list is a catalog of the quantities to be measured in flight tests. Typically, a measurements list contains as a minimum: the measurement name, range of values expected, accuracy, resolution, frequency response, location on the aircraft, environmental conditions, phase correlation with other measurements, flight period of importance, measurement priority, and remarks. This is prepared by the flight test engineer on the basis of the flight test program. The instrumentation engineer should be drawn in at an early stage and may contribute instrumentation-oriented requirements to the list. Figure 2.1 is an example of a measurements list. The exact form of the list may contain more or less information, depending on the complexity of the system. The measurements list is a good indicator of system cost, schedule, amount of data processing required, etc. A measurements list, being the common linkage between the flight test engineer and the instrumentation engineer, should be kept up-to-date and reflect all agreed changes.

Use of the measurements list. Just why is a measurements list so vital to the instrumentation engineer? It contains the essential information needed by the instrumentation engineer to begin the system design work. The design approach can be determined only after considering these requirements. The flight test engineer should provide a measurements list as early as possible in the program, though its formulation should not be rushed. It can be very helpful if complete. If incomplete, it can initiate only a partial -- and sometimes false -- start. Situations do occur where, in order to gain the advantage of lead time on development work, an early disclosure of even an incomplete list is advantageous. Such an incomplete list should be accompanied by an indication of what, in general, may come later. The measurements list may also show remarks to indicate that further experimental work will be needed before some of its information can be supplied as, for example, in the case of aircraft environmental conditions.

The instrumentation engineer should assume the responsibility for challenging the requirements imposed by the measurements list. This validation process is a constructive practice in which the flight test engineer must participate, and even though the conversation may at times become heated, it should be encouraged to continue. It has often been experienced that such discussions have led to solutions which did not require costly special equipment. The instrumentation engineer, in arguing for his position, acts to prevent excesses and special cases from being imposed through default. It must be understood, however, that the instrumentation engineer does not have the last word about the measurements list. The flight test engineer can insist and can, though sometimes at a very high cost, get every measurement he desires.

The instrumentation engineer will usually attempt to negotiate an adjustment of parameters on the measurements list (such as measuring range, accuracy, frequency response) so as to better match those of more commonly supplied or stock transducers. This can reflect in savings in both cost and time by allowing the use of units already in hand and calibrated. It is not unusual for this to be done, for typically, some of the parameter specifications result from analytical work only, and though calculated precisely, do not reflect actual flight test experience. Certainly, gross changes in parameter values are beyond the scope of this suggestion.

2.2.3 The overall design of the instrumentation system

In this section, only the general and organisational aspects of the design of a flight test instrumentation system will be discussed. The more detailed aspects will come out in the later chapters of this book.

It is convenient for this purpose to view flight test instrumentation in a broader sense than just the onboard equipment, and to divide the system into two parts, which are physically distinct and which are generally developed by different groups of engineers (Figure 2.2). They are:

- the data collection subsystem. This subsystem includes all measuring channels and their associated equipment, which must be designed to function under the often strenuous environmental

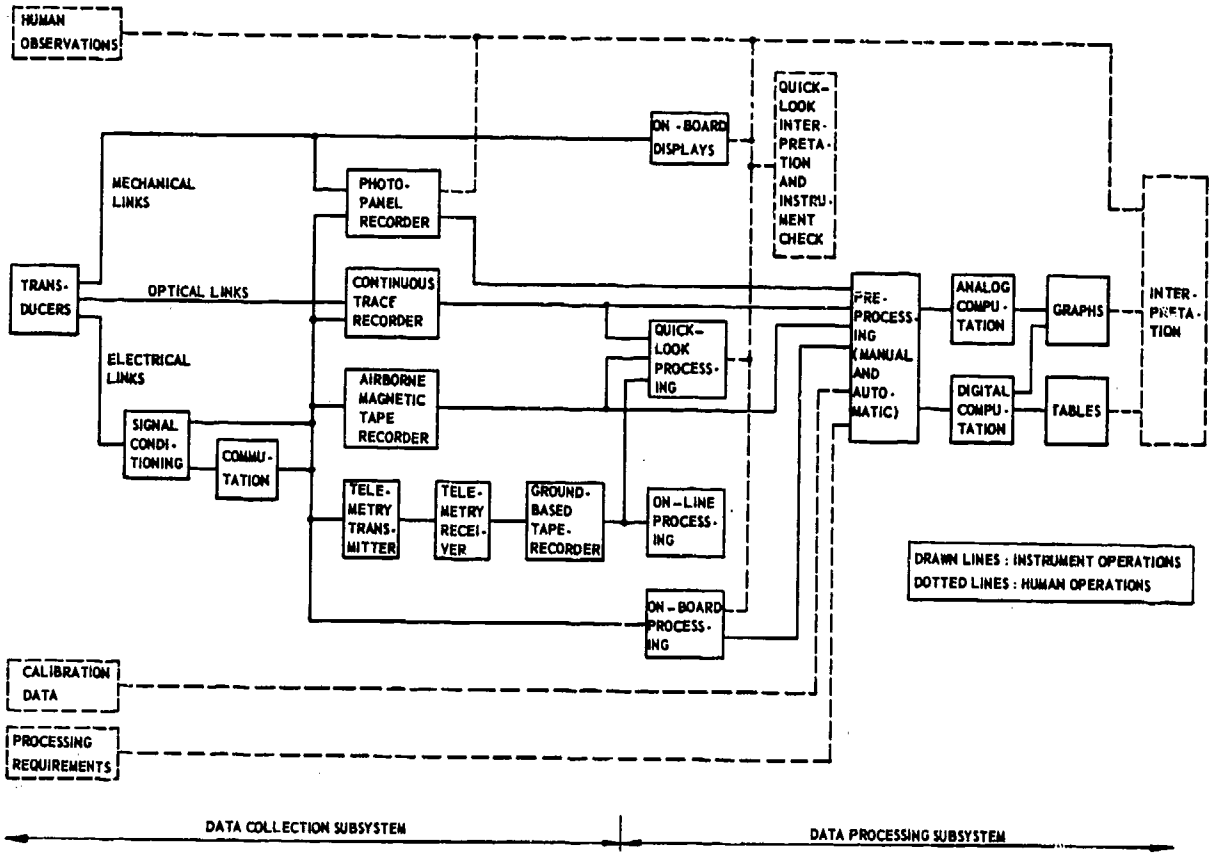


Figure 2.2 Block diagram of a flight test instrumentation system

conditions in the aircraft. This subsystem usually ends in a recorder, where the information is temporarily stored; some of the equipment used on the ground is often also regarded as part of this subsystem, for instance, the receiver and the ground recorder of a telemetry system, and even the measuring channels of any ground-based measuring equipment such as kinetheodolites.

- the <u>data processing subsystem.</u> The task of this subsystem is to convert the collected data to a form which is suitable for interpretation. This interpretation is usually done in two stages: first, a limited analysis is done as quickly as possible, in order to find out whether the tests have gone well and whether the data collection equipment has functioned correctly, which is the basis for the planning of the next flight; then a complete analysis begins, which must provide the test results in their final form. The data processing equipment is generally used in a well protected environment on the ground though, in a few cases, part of the analysis is already done in flight. For very simple tests involving only a few parameters, data processing can be done by hand. But in most flight test systems, a large amount of data processing equipment is used, including one or more computers with often complicated software.

An instrumentation engineer begins his work on the <u>data collection subsystem</u> by classifying the entries in the measurements list according to their frequency response and accuracy requirements. These two factors heavily influence the selection of the system approach. High accuracy requirements in combination with low-frequency requirements and a large number of parameters to be measured usually point towards a digital system. High-frequency response with low accuracy requirements and a not too large number of parameters can often be handled more easily with an analog system, especially if the interpretation of the flight test results can be done directly from a graphical representation of the time history of these parameters. High accuracy and high-frequency response for a large number of parameters will require a complex, costly system. If such a system seems necessary, a careful reconsideration of the purpose of the flight tests may sometimes show that the objectives can also be

reached with a less complicated system. A few high-frequency channels can often be accommodated in a digital system by using supercommutation, a few high accuracy channels can be made available in an analog system by using coarse-fine recording on two data tracks. If too many channels of both types are required, it may be necessary to use both analog and digital systems in the same aircraft.

By further sorting of the measurements list according to other requirements, such as the period in the test program when the parameter has to be recorded, its priority, etc., the instrumentation engineer will arrive at the number of parameters which must be recorded simultaneously. Here, two approaches are possible: the data collection system can record all parameters during all flights and the selection of the relevant data for each flight is done in the data processing system, or the system can be designed to record only the relevant parameters during each flight. If the first approach is used, a larger number of data channels will be required, which generally means that the airborne equipment will occupy more space; it has the advantage that all parameters are being recorded when an unexpected phenomenon occurs and is, at least in part, necessary if the modern flight test techniques mentioned in Section 1.3.1.1 are used. If the second approach is used, different parameters can be recorded alternatively on the same data track so that the physical dimensions of at least the recording system can often be markedly reduced; it then requires, however, a more complicated provision for switching different parameters to the same data channel and it will often require more time during the pre-flight and post-flight checks. In some types of flight tests, there are many parameters which need only be measured a few times during the flight test program. If the data processing is not too highly automated, it is often easier to have those parameters read during flight by human observers than to reserve separate data tracks for them. Another important step in the design of flight test instrumentation is the decision whether onboard recording or telemetry (or both) will be used. This decision is based upon factors such as data turnaround time, aircraft range during flight test, and potential hazard.

The more technical aspects of the general design are given in Chapter 8. It must be stressed that this development must be made in parallel with that of the data processing system, so that compatibility between the two subsystems is ensured. Also, the general lines of the calibration procedures must be laid down simultaneously. When the general design of the data collection subsystem has been agreed upon, the detailed design of each data channel can be started (see Chapters 3 through 6) and the calibration techniques (Chapter 7) and the recording or telemetry system (Chapters 9 and 10) can be chosen.

In parallel with the data collection system, the <u>data processing subsystem</u> must be developed. If only a few parameters are involved and if the operations which have to be done on these parameters are not too complicated, data processing by hand often provides the optimal solution. But, for most flight tests, the use of more automated data processing has become an essential requirement. The number of parameters which can be recorded simultaneously has increased enormously (to several thousand parameters), while the turnaround time of the data processing has remained constant or has even been reduced. These large amounts of data are usually recorded on magnetic tape (either directly onboard the aircraft or in a telemetry station) and can then be processed by computers. The larger number of parameters per flight and the increased computing capacity can be used to reduce the number of test flights for a given test program, and to flight test much more complicated aircraft in the same time as simpler aircraft types were tested previously. In the latest systems for the flight testing of aircraft, even the intermediate storage of the data on magnetic tape is no longer essential: telemetered data are processed on-line in high-speed digital computers and the data are immediately displayed to human observers on the ground to enable them to give real-time directions to the flight crew and to do the interpretation while the aircraft is still flying. This technique, which was already used in some cases for a few parameters when critical flight simulations were being explored, is now being used during the complete flight test program for increasing numbers of parameters (Refs. 4 and 5 of Chapter 1).

It is convenient to break down further the data processing into two phases: the pre-processing phase and the computation phase. In the <u>pre-processing phase</u> the data remain in the form of time histories of the different parameters, but many kinds of operations are performed on these time histories, such as: conversion to a computer-compatible format, selection of channels, filtering,

application of calibrations, etc. These are all more or less standard operations for all parameters. In many processing stations, especially those which receive many different types of inputs such as onboard recordings, telemetry data in different analog and digital formats, a special pre-processing computer is used for all or most of the pre-processing operations. At the end of the pre-processing phase, the data are usually recorded on a magnetic tape which is compatible with the input requirements of standard digital computers. In the computation phase, these data are then further processed to a state where they can be used for interpretation of flight results. This is usually done in a standard digital computer, which is often shared with other users. In many flight test programs, a preliminary stage of processing is required for quick-look and instrumentation checking. This provides time histories of a limited number of parameters, from which the quality of the flight tests can be estimated as a guideline for the planning of the next flight, and information from which anomalies in the instrumentation system can be detected. The main requirement for this phase is that the data must be available as soon as possible after the flight. Quick-look data are sometimes obtained by telemetering a limited amount of data to the ground, or by a special computer run of the data from the onboard recorders.

Data processing equipment is seldom bought for a single flight test program. It usually is already available before the design of the flight test instrumentation system begins. The main design aspect of data processing is, therefore, the production of the necessary software. During the design phase, the plans for the data processing program must be closely correlated with the flight test program, the capabilities of the data collection system, the organization of the calibrations, etc. During the development phase, the programming will be done by data processing specialists with close coordination with the instrumentation engineer. Ample time should always be reserved for testing and optimising the software, using inputs from the actual data collection hardware as it becomes available.

2.2.4 Other factors of influence on system design

In the design of an instrumentation system for flight testing, a number of aspects must be taken into account which have not yet been discussed in detail. The most important of these are listed in Figure 2.3, and are briefly discussed below.

Cost. The cost of a flight test instrumentation system is directly related to the requirements imposed. An instrumentation system designed to satisfy only the requirements of a given flight test program will have a basic cost. Below this basic cost, performance of the system will be degraded or capability eliminated. Accuracy has, perhaps, the most important influence on cost. A 5 percent overall accuracy is relatively easy to obtain from analog recording and telemetry systems; 1 percent is a very difficult goal for analog systems, but is easier to obtain from digital systems. Accuracies of the order of 0.1 or 0.2 percent, which are often requested by flight test engineers, are very difficult to obtain even with digital systems. A very careful consideration of what accuracy is really needed should precede the design of any new instrumentation system.

The inclusion of optional items may contribute significantly to the overall cost of the system. It must be kept in mind, however, that for a system which can be used for other

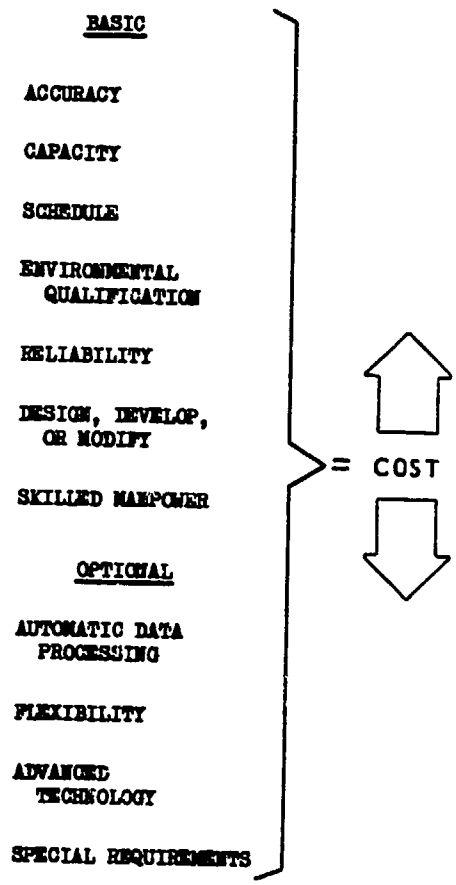


Figure 2.3 Factors that effect system cost

tests as well, the initial cost may be higher but the cost per aircraft may be low. One of the difficulties of financing advances in instrumentation systems is the reluctance of flight test engineers to provide funds for requirements beyond their immediate needs. Separate battles must be waged by instrumentation organisations to get funds for improving the instrumentation capability. Experience has taught that one of the best cost-control techniques is the careful review of the need for every data channel requested , including an evaluation of its anticipated value. If the program can be accomplished using conventional techniques, this should be seriously considered.

Development or modification. From an examination of all requirements, a decision must be made regarding how much of the requirements can be satisfied using existing systems or components of those systems. If existing system capabilities prove to be inadequate, modifications (such as the addition of channels, increase in sampling rate, etc.) can be considered. Modifications are not always successful, but the fact that the accumulated experience with the old system can be applied to the new system is an enormous advantage. With a new system, risks are always involved, especially when the development is scheduled. Ample time should be reserved to gain experience with a new system and to test it under laboratory and flight conditions.

Schedule. Flight test instrumentation systems are in many cases developed under a very tight schedule. In practice, it is usually very late in the development of an aircraft or of an operational procedure that the measurements list can be made up. A flight test program schedule prepared without consultation with the instrumentation engineer is deficient from the outset. An adequate amount of time in the schedule must be allocated, especially if new systems are to be developed, because many unexpected delays tend to occur. In certain situations, making preliminary program requirements known to the instrumentation engineer will permit him enough lead time to begin the development work.

Flight test programs dependent on the development of a new system must either provide enough time in the schedule or sustain additional cost due to extra manpower and overtime work.

Personnel. The design phase must be executed by highly qualified personnel of the flight test instrumentation department. For the development phase, subcontracts can be let to the industry, but a design team must be available to supervise it.

Not only the personnel involved in the design and testing must be highly qualified, the same also applies for the personnel which must maintain and check the instrumentation system during its operation. Ample time in the test phase must be reserved for training this personnel. This training must not be limited to just routine operations. The maintenance crew should know as much as possible about any weak points in the system and alertness should be stimulated to detect errors and system deficiencies. A qualified and well trained maintenance crew is an important aspect for attaining program success.

Accuracy. The accuracy of flight test data does not result from the transducer accuracy alone, but is dependent upon maintaining accuracy throughout the instrumentation system. Verifying overall accuracy adds to the analytical phase of the design in that special tests on all components processing the signal must be made, precision calibration methods must be developed, and the data collection, pre-processing and processing subsystems must qualify to a more demanding specification. Experimental verification of the overall accuracy in the test phase will also require much time and expenditure of funds.

Environmental qualifications. An important aspect of the overall accuracy is that it must be reached under the environmental conditions present in the aircraft. These include pressure, temperature, vibration and shock, but also such other aspects as electrical and radio interference, power system noise, etc. The difficulty especially with these latter effects is that they are difficult to estimate beforehand. Even though many precautions like shielding and optimal points for ground connections can be taken during the design phase, only actual tests in the aircraft can show whether these have succeeded and what further measures need to be taken.

Reliability. Reliability is built into a flight test instrumentation system by using quality components that have undergone a suitable test program and have a flight history similar to that of the intended application. Reliability is further ensured through good workmanship, inspection, and good system design.

Another aspect of reliability is safety. Flight tests vary in the dangers to which the aircraft and its occupants are exposed. An attempt to minimize these dangers can place special requirements on the reliability of instrumentation systems which will be reflected in cost and schedule. Special safety measures will also have to be taken when the instrumentation system is connected to the circuits of the pilot's instruments or to essential systems in the aircraft. If flight parameter values are extremely critical, safety monitoring by telemetry or by onboard observers may be needed. Requirements such as this should be identified in the program beginning.

Maintenance. Every system designed and built will require maintenance in its lifetime. Planning for this during system design is essential. Maintenance schedules should be set up early. The judicious selection of places to insert test points for performing electrical checks without disturbing the system will pay for the effort expended during the design. The placement of test points for convenience can be as important as the existence of the test points themselves. Routine maintenance, such as cleaning recorder heads or replacing oscillograph paper, will, of course, be performed without using test points, but the real use of such maintenance aids comes when something fails to function. Fault isolation is greatly aided through the use of appropriately located test points, built-in or portable test equipment capable of generating calibration signals, and through the location of functional portions of subsystems in physically separate modules. In this way, complete functions can be expeditiously replaced.

Accessibility. The efficiency of maintenance procedures can be impeded if the components in the system are inaccessible when built into the aircraft. The location of test points and adjustable devices which must be readily accessible for maintenance must be planned, as to its most advantageous position in the aircraft. In prototype aircraft, additional facilities are often provided for the instrumentation, which will not be provided in production aircraft. This must be planned at an early stage, so that the instrumentation requirements can be accommodated during the modification of the test aircraft.

Flexibility. Flexibility is the designed-in capability of an instrumentation system to be changed to meet differing flight test requirements and situations. The objective of flexibility is to minimize the amount of change required in an instrumentation system as a result of large changes in a flight test program and even to adapt it to other flight test programs in other types of aircraft. Though a "universal" flight test instrumentation system would be both too costly and ineffective, a system designed to satisfy a number of flight test programs and types of aircraft can be cost effective and the least obstacle in a fast-paced schedule. Flexibility cannot be limited to system capacity and electrical characteristics. If more than one aircraft type is to use it, the instrumentation system will also need flexibility in its physical design.

Standardization of designs, components, and layout and construction at the subsystem level or lower, contribute to system flexibility. For example, a system can be designed and constructed in the form of a compatible set of modules or printed-circuit plug-in cards and be used to assemble several flight test instrumentation units without the need for a complete new design. For pre-processing and processing systems, which involve large capital investments, flexibility is essential.

Standardization, in general, aids maintenance personnel through familiarity gained by repeated use, contributes to lower cost through quantity purchases, and requires less redesign. The repeated flight experience of components and subsystems provides realistic reliability information and increased confidence.

2.3 CONCLUSION

The subjects introduced in this chapter represent the logical first order of business in the design of an instrumentation system in that goals must be established before detailed design can begin. From this point forward, design specialists must decide how best to fulfill the stated requirements. There are many significant technical decisions to be made before a complete system can be realized. Sensors, transducers, signal conditioning techniques, and electronic hardware must undergo careful analysis and laboratory testing. Software must be programmed and tested. In the following chapters of this book, the detailed design of instrumentation systems will be discussed.

2.4 REFERENCES

1. Harry L. Stiltz — Aerospace Telemetry, Vol. I, Prentice-Hall, Inc., 1961.

2. Harry L. Stiltz — Aerospace Telemetry, Vol. II, Prentice-Hall, Inc., 1966.

3. C. den Hartog — Application of Aircraft Integrated Data Systems, AGARD Report 561, December 1967.

4. Flight Test Instrumentation, AGARD Conference Proceedings 32, 1967.

5. R.E. Machol — System Engineering Handbook, McGraw Hill Book Company, 1965.

6. L.S. Hill — System Engineering in Perspective, IEEE Transactions on Engineering Management, Vol. EM-17, No. 4, November 1970.

7. Report of the Weapon Systems Effectiveness Industry Advisory Committee, January 1965, Air Force Systems Command, Andrews Air Force Base, Maryland, U.S.A.

CHAPTER 3

METROLOGICAL CHARACTERISTICS OF A MEASURING CHANNEL

by

J. Idrac

3.1 INTRODUCTION

The success of a flight test operation, and in fact, of every operation involving measurements, depends on whether the measured data represent the values of the measurand at the moment of measurement with sufficient accuracy. As the number of possible technical solutions of a measurement and the complexity of the measuring equipment increase, the design of such equipment more and more becomes a matter of team work of several specialists. Such team work can only provide optimal results if all specialists use the same language, i.e. if the same terms convey the same concepts to all. In the past, this has often not been the case, largely because many flight test engineers do not have a sufficient understanding of the language of the instrumentation engineers. In this chapter an analysis will be given of the fundamental characteristics of a measuring process and all concepts will be carefully defined. The more technical aspects of the design of a measuring channel will be discussed in Chapters 4 to 7.

A measuring channel as considered in this chapter can be a simple pointer instrument or a complex assembly of several airborne "black boxes" such as a transducer, a signal conditioner, a commutator, an analog-to-digital converter, an indicator or recorder, etc. and often of some of the associated ground equipment. The main metrological characteristics of such a measuring channel are:

- measuring range
- sensitivity
- linearity
- accuracy.

The accuracy must be regarded under three aspects:

- static accuracy
- dynamic response
- finesse.

These characteristics will be discussed separately in this chapter. Before doing this, it will be useful to give a short analysis of the (mental) steps involved in a measuring operation (Section 3.2) and to define a few terms relating to errors (Section 3.3).

3.2 PHASES IN A MEASURING OPERATION

In order to illustrate the mental processes involved in making a measurement, an analysis will be given of a manual measuring operation. Although in automatic measurements the emphasis may be slightly different in some of the phases, such measurements in principle follow the same procedure.

Phase 1. Obtaining a rough reading

The first step in a measuring operation is to obtain a numerical value. This may be done, for example, by writing down the position of a pointer relative to a scale on a dial, by measuring the position of a trace on a continuous-trace recording, or by storing a digital number in a computer memory. The number so obtained often is not expressed in units of the measurand. For instance, the output of a pressure transducer can be read in Volts from a voltmeter, in digital figures from a digital indicator, or in millimeters from a continuous-trace recording.

Phase 2. Conversion of the rough reading into an indicated value

In this phase the rough reading is converted into a number expressed in units of the measurand. The relation between the rough reading and the indicated value is given by the static calibration. For pointer instruments where the scale is graduated in units of the measurand, phases 1 and 2 coincide.

Phase 3. Correction of the indicated value to the measured value

These corrections take into account previously measured or calculated imperfections of the measuring chain. The corrections may be derived from more precise static calibration data (for instance corrections relative to the scale of a pointer instrument), from the dynamic characteristics of the

measuring chain, from environmental effects, etc. The sign of such corrections is such that

indicated value + correction = measured value. (3.1)

Phase 4. Calculation of the most probable value

If more than one measured value of the same measurand is available, it will often be possible to use statistical methods to obtain a more accurate result. Two cases are considered here:

- a number of measurements have been made under (essentially) the same conditions. Then the mean of these measured values will be the most probable value
- a time history is available of a process in which the measurand changed relatively slowly. In that case, a smoothing technique will produce the most probable values of the individual measurements.

These statistical methods can also give an indication of the uncertainty which remains in the most probable values. As discussed in more detail in Section 3.3, statistical methods do not reduce the effects of any systematic errors not corrected in phase 3, above.

Phase 5. Meditation about the true value

When analysing the results of a measurement, the engineer must think about the significance of the most probable value. There may be systematic errors which have not been corrected. Also, an instrument never directly measures the quantity in which one is interested: a strain gauge does not measure the strain at a certain point in the structure but the average elongation of the surface area to which it is bonded; a thermometer does not measure the air temperature at a certain point in space but the average temperature of its probe, etc. Peaks in a time history may be reduced or even completely suppressed by the dynamic response of the measuring system. Many similar effects may cause differences between the most probable value of the measured quantity and the true value of the quantity in which one is interested. Although these points should all have been considered during the design of the measuring chain (on the basis of predicted inputs), it is essential that they are reconsidered when interpreting the results of the measurement. Then the engineer must clearly remember the simplifying assumptions accepted in the design phase and reconsider them in the light of the measuring results obtained.

3.3 ERRORS IN A MEASUREMENT

The term total error in a measurement is used for the difference between the true value and the measured value (or the most probable value). The word error is used for components of the total error, due to single effects influencing the measurement accuracy, such as hysteresis error, temperature error, dynamic error, etc.

Errors are stochastic quantities, i.e. they are characterized by a probability distribution but their exact value in a certain measurement is not known. If the exact value should be known, a correction can be applied to the measurement and the resulting error will be zero. In many cases the value of the errors can be reduced by a deeper analysis of the measuring channel and its environment. For instance, a temperature error can be reduced if the temperature is measured and a correction applied. To a certain extent the magnitude of the error is, therefore, a matter of choice by the instrumentation engineer. As the analysis of errors is costly, it will not be extended further than is necessary for the success of the measurement.

The analysis of errors must be based on the results of:

- a thorough test programme with the instrument (or with one or more instruments of the same type), in which the probability distributions of the errors (such as reading error, friction error, etc.) are determined, as well as the sensitivity to error-producing effects (such as temperature effect, dynamic response, etc.)
- periodic recalibrations and checks, from which failures of the instrument can be detected and from which in some cases new values of corrections and errors can be obtained
- measurements of the error-producing quantities (such as temperature, vibration, etc.) or estimates of their probability distributions.

If the probability distributions of all errors are known, the probability distribution of the total error can be calculated by statistical methods. These methods are described in many books on statistics. Here three statistical characteristics will be discussed briefly. They are:

- the average or systematic error
- the shape of the probability distribution curve
- statistical dependence of errors.

A systematic error occurs if the average value of the error differs from zero. Systematic errors can have a large influence on the accuracy which can be obtained. If values of the systematic errors are known, they can be applied as a correction, so that the remaining error distribution has a zero average.

The shape of the distribution curve can be different for different types of errors. Many errors have a distribution which closely approximates the normal or Gaussian distribution. Handbooks of statistics give tables and equations for these distributions. If they have zero average, they can be characterized by a single parameter, the standard deviation σ. If all errors have normal distributions and are statistically independent the total error calculated from them will also have a normal distribution. The standard deviation of the total error σ_t can be calculated from the standard deviations σ_i of the individual errors by

$$\sigma_t = \sqrt{\sigma_1^2 + \sigma_2^2 + \sigma_3^2 + \ldots\ldots} \qquad (3.2)$$

The probability that an error with a normal distribution is not larger than σ is 68.3 %, that it is not larger than 2σ is 95.5 % and that it is not larger than 3σ is 99.73 %.

Many errors have non-normal distributions. One example is the quantization error which occurs, for instance, in digital outputs. The measured value is rounded off to the nearest of a number of discrete, equally-spaced output values and the true value may with equal probability lie anywhere between $\pm$ half the least significant bit. If all errors have the same type of non-normal distribution, the total error distribution will not have the same shape. Although equation (3.2) remains valid, the relation between the standard deviation and the probability distribution will be different for different types of distributions. In practice equation (3.2) is then still used and it is tacitly assumed that the distribution of the total error is sufficiently like a normal distribution so that the probability values for σ, 2σ and 3σ are the same. This is often a good approximation, but in extreme cases the true probability values can be considerably different.

If the errors are dependent, equation (3.2) is not valid. In that case there is a definite relation between the values of two or more errors. The important concept of dependence will be illustrated by two examples. An amplifier may have a "zero offset" and an error due to an incorrect supply voltage. These errors may be uncorrelated and therefore independent. Both errors may, however, be caused by the same temperature effect for which no correction is applied; in that case they will be dependent. They will also be dependent if they both vary linearly with time. Another example of dependence can be found in an air-damped instrument. The dynamic response of this instrument will vary with temperature (due to changes in the dimensions of the air gap) and with pressure (due to the change of friction with pressure). If the instrument is exposed to the ambient air around an aircraft, there will be a correlation of temperature and pressure with altitude. For tests at different altitudes the temperature and pressure effects on the dynamic response of the instrument will therefore be dependent. If dependence occurs, the law governing the dependence must be taken into account in the statistical calculation of the total error. If the errors are linearly dependent, the errors (and their standard deviations) must be added algebraically.

In many specifications a single value of the total error is given. Usually this will be a 3σ value, but in some cases a 1σ value is meant or, if the total error distribution is truncated, it may be the maximum value. For a correct error analysis it should always be specified what type of error is meant.

One type of error that must still be mentioned is the blunder. This can, for instance, be due to a mistake in reading an instrument, to a temporarily loose contact in an electrical circuit or to an incorrectly punched bit in a digital paper-tape output. The values in most cases lie so far from all others that they can be easily detected and eliminated during manual data processing. In automatic data processing in a computer they can cause problems if no special measures have been taken in the programme to eliminate them (see Chapter 12).

Errors are usually given in percent of the full-scale value (°/o FS). In some cases they are given as percent of the measured value or as a number of units of the measurand.

3.4 MEASURING RANGE

The first information which an engineer asks about an instrument is the range of values of the input parameter which it can measure: its measuring range. For example, a thermometer can have a measuring range from - 50 °C to + 50 °C.

The normal measuring range is the range of values of the measurand which the instrument can measure with the accuracy, sensitivity and linearity specified for it.

For many instruments ranges of environmental parameters (such as temperature or vibration) are also specified. The manufacturer guarantees that the accuracy will be within specified limits as long as the environmental parameters stay within these ranges.

Many instruments can be damaged if they are subjected to an input outside their measuring range. For such instruments a maximum overload is often specified. If the input parameter has attained values higher than the maximum overload, the manufacturer no longer guarantees the accuracy within the normal measuring range. The maximum overloads at the two ends of the measuring range may be different. If an overload lower than the maximum overload has been applied, the instrument may need a certain recovery time before it will function properly after the overload has disappeared.

Maximum overloads for environmental parameters are sometimes specified, for instance, if the instrument can be damaged by extreme values of temperature, vibration or shock. If the instrument has been subjected to environmental conditions (temperature, pressure, vibration, shock) outside the normal range but within the maximum overloads, then it should again operate according to its specification when the environmental conditions return to their normal range. These maximum overloads are sometimes specified separately for operating conditions (i.e. the instrument should continue to function, though with degraded performance) and for non-operating conditions (storage, transport).

3.5 SENSITIVITY AND LINEARITY

A second important characteristic of a measuring channel is its sensitivity. This is the ratio of a difference in the output and the corresponding difference of the input of the channel. It can be easily understood from the static calibration curve (Fig. 3.1). The sensitivity at a certain point is the slope of the tangent to the calibration curve at that point. In Figure 3.1 the sensitivity is expressed in $\frac{\text{Volts}}{\text{N/m}^2}$.

In general the sensitivity of a measuring channel is not constant for the complete measuring range. In such cases the best straight-line approximation to the calibration curve is often determined (by hand-fitting or by the least-squares method). The slope of this line is the average sensitivity over the measuring range. This average sensitivity is often used for quick-look data analysis. For the case of Figure 3.1 a first approximation of the pressure can be obtained from

$$P - P_o = \frac{V - V_o}{\bar{S}} \qquad (3.3)$$

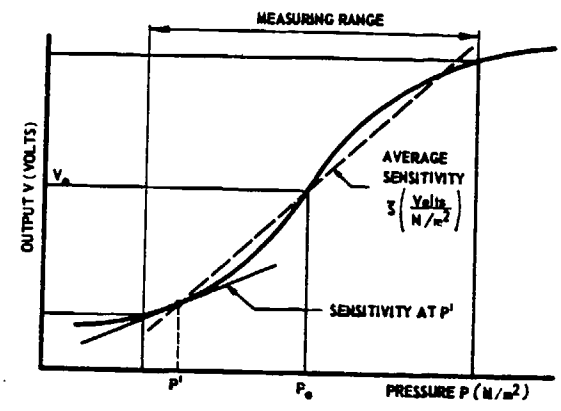


Figure 3.1 Static calibration curve of a typical pressure transducer

Equation (3.3) is often used as a first step in calculating the input value from the measured data, especially if data processing is done by hand. A graph of the type of Figure 3.1 must be drawn to a large scale if it must be read to an accuracy of 1 °/o FS or better. It is often simpler to use a correction graph of the type of Figure 3.2, which gives the difference between the true calibration and the straight-line approximation on an expanded scale. The correction C(V) is then added to the first approximation of eq. (3.3):

$$P - P_o = \frac{V - V_o}{\bar{S}} + C(V) \qquad (3.4)$$

If the sensitivity is constant over the complete measuring range, the measuring channel is statically linear. The word "statically" is added to distinguish it from dynamic linearity, which is defined in Section 3.8. For instruments which are not statically linear, the non-linearity is often mentioned in the specification. This is defined as the maximum difference between the calibration curve and its linear approximation, divided by the measuring range. It is expressed in percent of the measuring range (°/o FS).

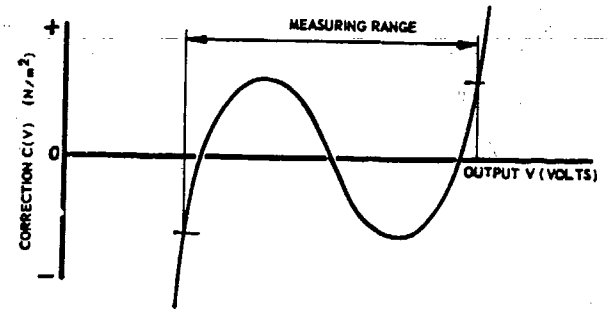


Figure 3.2 Correction curve for the transducer of Figure 3.1

The word sensitivity is sometimes used for a different quantity: the smallest change in the measurand which can be detected by the instrument. The normal term for this is resolution, which should be used for this purpose to prevent confusion (see also Section 3.7).

3.6 ACCURACY

The accuracy of a measuring chain is a quality which is determined by the value of the residual total error after a reasonable amount of correction has been applied. From this definition it follows that the accuracy of a given instrument is not an entirely fixed value: if more effort is made in determining corrections, the accuracy can be increased somewhat. It will, however, never be possible to eliminate all errors and beyond a certain point the effort required to obtain even a small increase in accuracy will be tremendous. Such an effort may be justified for primary calibration standards, but the cost of additional accuracy will often not be economically acceptable for normal flight tests. In exceptional cases, however, a slight increase of the accuracy over that claimed by the manufacturer can be justified. Generally, this applies to instruments manufactured for operational use in aircraft, as for instance altimeters. The manufacturer's accuracy claims are based on the use by the flight crew, who cannot apply corrections to the scale readings during flight. If such instruments are used for special flight test purposes, an individual calibration of each instrument may increase the accuracy slightly over the value claimed by the manufacturer.

The determination of the accuracy of a measuring channel can in principle be done in two ways. In the "a-priori method" the errors are determined by tests before the actual measurement as discussed in Section 3.3 and the corrections and residual errors are determined from these tests. In the "a-posteriori method" the average value and the accuracy are determined by statistical analysis of multiple measurements. In general, both methods are applied together: systematic errors, which cannot be corrected on an a-posteriori basis, must be determined by the a-priori method, but the final accuracy can be increased by taking an average of a number of measurements or by smoothing.

It is convenient to divide the discussion of accuracy into three parts:

- static accuracy, which involves the errors which occur when the measurand changes so slowly that the frequency response of the measuring channel does not significantly influence the accuracy. Measurements under these conditions are often called quasi-static, as low-frequency changes can be allowed
- dynamic accuracy, which involves the errors which are caused by the dynamic response of the measuring channel
- finesse[x)], which involves the errors caused by the fact that the presence of the instrument modifies the phenomena which must be measured.

These three categories will be discussed separately.

---

x) The English language does not have a single word to denote this concept. The French use the word finesse. In discussions with several British and American instrumentation specialists it was found that they liked the use of the word finesse for this concept. Accordingly, this word will be employed in this book.

3.7 STATIC ACCURACY

Under quasi-static conditions there are many effects which can cause errors. The types of errors and the effect of each type of error on the measurement vary for different instrument types. The following division of static errors has been found to be convenient in practice:

1. Reading error. This is the error made during the reading of the output signal. It includes the errors due to the limited sensitivity of the reading device (which can be the humen eye or the reading system of a tape recorder) to parallax, to interpolation, to background noise, etc.
2. Dead-band error. This error is due to the fact that the output signal of the measuring chain does not change with small changes of the input parameter. This error can be caused by friction, by play in gears, by the fact that the output signal can only appear in discrete steps. This latter phenomenon can be caused, for instance, by steps from one wire to the next in potentiometers or by the digitizing of signals (quantization error).

The sum of the errors of these two types is called the resolution, already mentioned at the end of Section 3.5.

3. Hysteresis error. If the relation between input and output is determined for both increasing inputs and decreasing inputs, it is often found that the output at a given input depends on the direction in which the input was varied. This is called hysteresis. This error is not completely independent of the dead-band error, as friction and play in gears can also cause hysteresis errors.
4. Errors due to environmental conditions. These include errors due to temperature, thermal shock, pressure, electro-magnetic fields, acceleration, vibration, shock, duration of the measurement, ageing, supply voltage and frequency, etc.

The sum of the errors of types 1 to 4 is called the reproducibility error.

5. Zero error. This error is only taken into account separately if the zero point can be set manually, as in altimeters, ohmmeters, etc. In other cases the zero error will fall under the errors due to environmental conditions or under the calibration error.
6. Calibration error. This is the error made when applying the calibration data. For pointer instruments where the scale engraved on the dial is used without additional calibration data, this error is called the scale error.
7. Error of the calibration standard. This is the error made in the determination of the reference quantity, which is measured during calibration by the calibration standard.

Many of the errors mentioned depend on time. There are, basically, three ways in which this time dependence can occur:

- the error may be correlated with the time history of the signal itself, as with the hysteresis error. Although these errors can, in principle, be corrected (at least partially), this requires a time-consuming procedure and is usually not done.
- the error can be correlated with parameters other than its input signal. The most common example of this is the variation with time of environmental conditions such as temperature, pressure and vibration during a flight. Another example is the effect of components of the input quantity along axes other then the nominal measuring axis, in instruments which are subject to cross-axis sensitivity (see Section 4.2.2). These errors can be corrected if the influencing parameters are measured.
- the error can be (virtually) uncorrelated with any parameter other than time. The main cause of these errors is ageing of the components of the instruments. These errors are called drift errors, the characteristic describing them is the stability of the instrument. In some cases a short-term stability and a long-term stability are specified. The short-term stability is then the stability during a period typical for the type of measurement, for instance during one flight. The long-term stability applies to the change of calibration over the life of the instrument. It must be pointed out that the word stability is also used in another sense: the characteristic of a system to go back to its state of equilibrium (e.g. stability of a servo system). The distinction between these two meanings of the word stability should be clearly kept in mind to avoid confusion.

As previously mentioned, the accuracy obtainable in a measurement with a certain instrument depends on many factors, such as the effort made in determining corrections of errors, the variations in environmental conditions and the number of measurements which can be used to determine the most probable value. It is, therefore, a practical impossibility to characterize the "accuracy of an

instrument" by one or a few numbers. Values, given by manufacturers, in instrument specifications are often grossly misleading because they have been determined under favourable conditions never encountered in the actual operation of the instrument. Efforts are now being made to come to standardized accuracy definitions, which will make it possible to make a first choice between different instruments by comparing short specifications. This has advanced farthest in a few specialized fields (such as electrical instruments, Ref. 2) and in some countries (France, Ref 1). The instruments are classified in "Accuracy classes" such as class 5 %, class 1 %, class 0.25 %, class 0.1 %. This standardization is very useful if all concerned clearly understand its limitations. The classifications consider static accuracy only.

3.8 DYNAMIC ACCURACY

If a measuring channel is subjected to rapidly varying inputs, the relation between input and output becomes different from that in the quasi-static case. The dynamic response of a measuring channel can be expressed in a differential equation. If this is a linear differential equation, the channel is dynamically linear. Because the analysis of dynamically non-linear systems is much more difficult, the corrections obtainable with the same amount of effort are much less accurate for dynamically non-linear systems than for linear systems. Therefore, the designers try to achieve dynamic linearity in all instruments for which the dynamic response is important. Although absolute linearity will never be completely achieved, it is sufficiently approached in most cases to make linear analysis possible within the accuracies required. The basis dynamic characteristics depend on the order of the differential equation of the instrument.

First-order instruments (which include, for instance, many temperature probes) can be characterized by one parameter, the time constant τ. The differential equation then is

$$\tau\dot{x} + x = y(t), \qquad (3.5)$$

where $y(t)$ = the time function of the input,

x = the output of the instrument.

The time constant is expressed in seconds.

Many transducers have a second-order characteristic. They can be characterized by two parameters, for which the natural frequency ω_o and the damping coefficient λ are normally used. With these parameters the differential equation takes the form

$$\frac{1}{\omega_o^2}\ddot{x} + \frac{2\lambda}{\omega_o}\dot{x} + x = y(t). \qquad (3.6)$$

Here ω_o is expressed in rad/sec and λ is non-dimensional.

Higher-order systems often occur when more than one lower-order system is used in series: if the output of a second-order transducer is fed to a second-order filter, the output of the filter will be related to the transducer input by a fourth-order equation.

The parameters mentioned above for the first-order and second-order instruments are very useful when analysing the response to simple input time functions. This will be illustrated for three types of input functions:

- a step input
- a linear variation of the input with time (ramp input)
- a sinusoidal input.

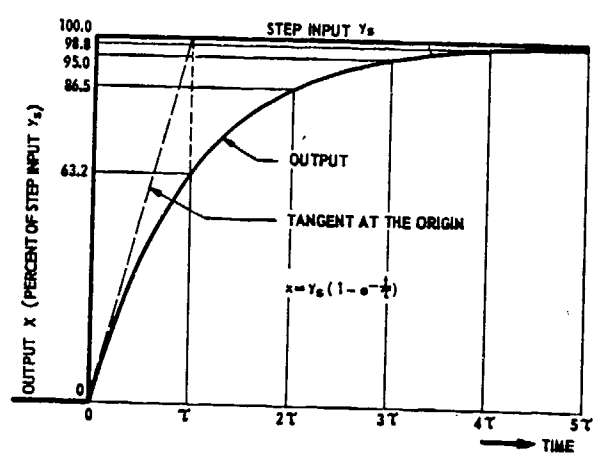


Figure 3.3 Response of a first-order system with time constant τ to a step input

The response to a step input of a first-order instrument is shown in Figure 3.3. The time constant is the time in which the error of the output function is reduced to a factor 1/e or to 37 %. After 2τ the error of the output function is reduced to 0.37^2 or about 14 % of the step value and after 3τ to 0.37^3 or 5 %. The response of a second-order system to

a step input has a different shape for different values of the damping coefficient (Figure 3.4). If $\lambda \geqslant 1$ the output approaches the input function without overshoot; the damping is <u>aperiodic</u>. If $\lambda < 1$ the output overshoots the input and returns to it by a damped oscillation. If $\lambda = 1$, it is said that the system is <u>critically damped</u>. For $\lambda = 0$ an undamped sinusoidal output is obtained with a frequency equal to the natural frequency.

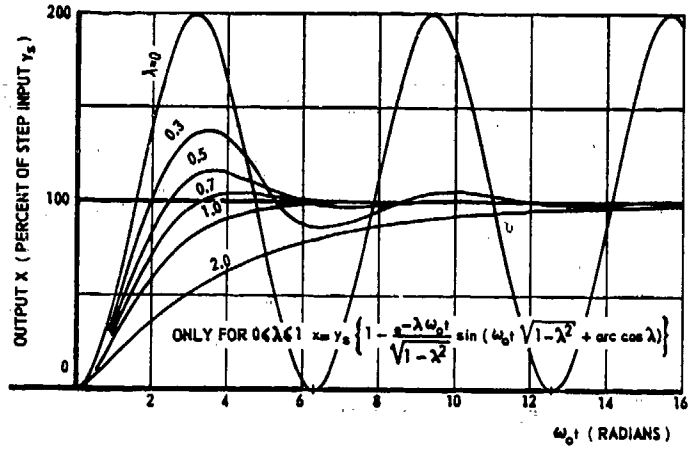


Figure 3.4 The response of second-order systems to a step input

The <u>response to a ramp input</u> of a first-order system is, after a short initial period, an output parallel to the input function but delayed by a time equal to the time constant. For a second-order system the delay time is equal to $2\lambda/\omega_o$.

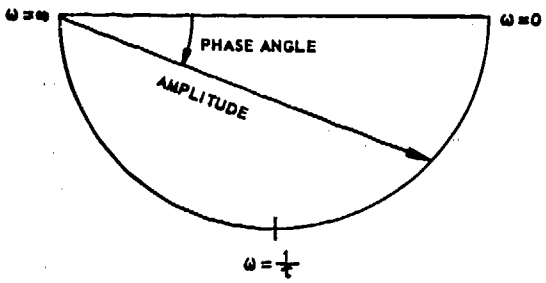


Figure 3.5 Polar representation of the frequency response of a first-order system

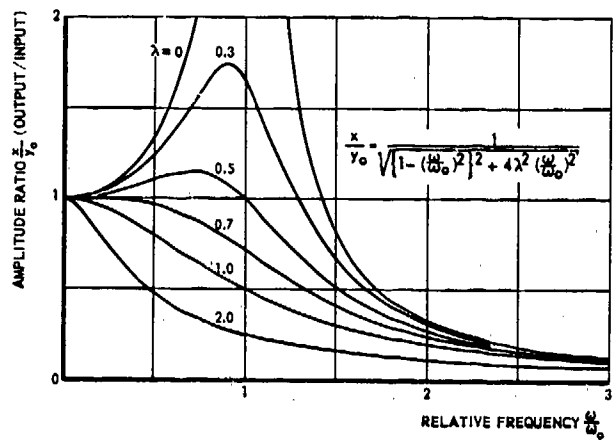


Figure 3.6 Amplitude characteristics of second-order systems

The <u>response to a sinusoidal input</u> of a first-order system is a sine wave which is shifted in phase relative to the input function and has a different amplitude. The phase angle is equal to $-\arctan \tau\omega$ (where ω is the radial frequency of the input function in rad/sec) and the ratio of output to input amplitude is equal to the cosine of the phase angle. The phase angle and the amplitude ratio can be read from the polar diagram developed by Nyquist (Figure 3.5). For a second-order system the amplitude ratio and the phase shift are given in Figures 3.6 and 3.7 as a function of the damping coefficient and of the relative frequency ω/ω_o. At relative frequencies much higher than 1 the amplitude response curves, drawn to a logarithmic frequency scale as in Figure 3.8, all approach asymptotically to the straight line $1/\left(\frac{\omega}{\omega_o}\right)^2$ for all values of the damping factor. This is often expressed by saying that the power spectrum rolls off at 12 dB/octave in this region. It is generally found that the amplitude response of a system of order n at relative frequencies $\frac{\omega}{\omega_o} > 1$ asymptotically approaches to a curve proportional to $1/\left(\frac{\omega}{\omega_o}\right)^n$, i.e. rolls off at n x 6 dB/octave; for a first-order system it is 6 dB/octave, etc.

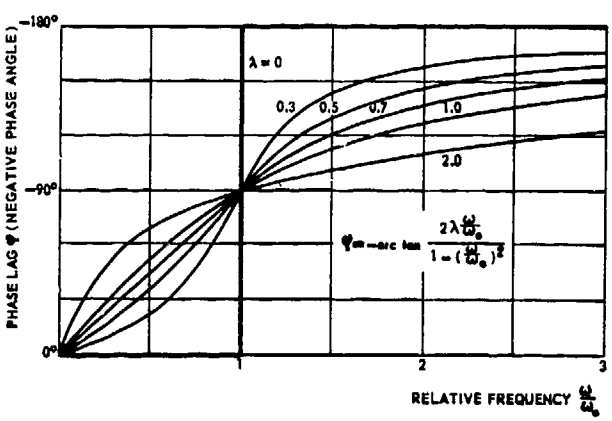


Figure 3.7 Phase characteristics of second-order systems

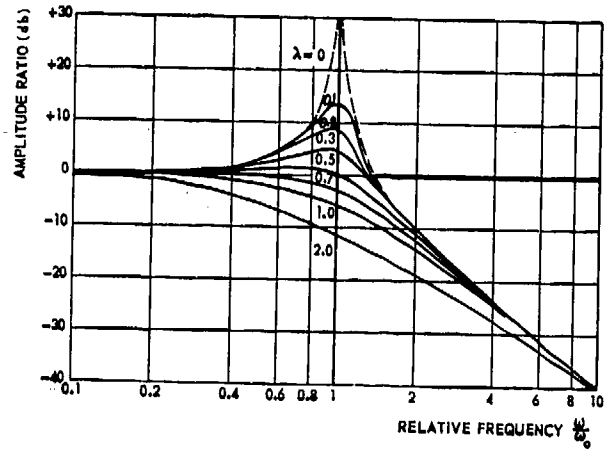


Figure 3.8 Amplitude characteristics of second-order systems drawn to logarithmic scales

We have considered the response of first-order and second-order instruments to special types of input time functions: a step input, a ramp input and a sinusoidal input. Now the more general case of the <u>response of a linear instrument or measuring channel of any order to an arbitrary input will be considered</u>. For every linear instrument the dynamic response characteristics can be given by an <u>amplitude curve and a phase curve</u> similar to those given in Figures 3.6 and 3.7. In the theory of Fourier analysis it has been shown that each arbitrary input time function, periodic or non-periodic, can be regarded as the sum of an infinite number of sinuoids each with a specific amplitude and phase. The output of the instrument to an arbitrary input time function can now be determined by first decomposing the input function into a sum of sinusoidal functions, then multiplying the amplitude of each sine wave with the amplitude response factor given by the amplitude curve at that frequency and shifting its phase by the amount given by the phase response curve at that frequency, and then summing all resulting sinusoids again.

This procedure will be given in a more mathematical form. For a detailed derivation handbooks on instrumentation theory should be consulted, such as References 3 and 4. The input time function can be represented by means of the Fourier integral:

$$S(\omega).e^{i\psi(\omega)} = \frac{1}{2\pi}\int_{-\infty}^{\infty} G(t).e^{-i\omega t}\,dt. \qquad (3.7)$$

Here G(t) is the input time function, $S(\omega)$ is the modulus which represents the amplitude variations as a function of the frequency and the exponential part on the left side represents the phase shift $\psi(\omega)$ which is again a function of frequency. The dynamic response of the instrument modifies the amplitude and phase of each sinusoid in a way expressed by its <u>transfer function</u>

$$H(i\omega) = A(\omega).e^{i\,\varphi(\omega)}. \qquad (3.8)$$

The output time function of the instrument is then

$$Y(t) = \frac{1}{2\pi}\int_{-\infty}^{\infty} H(i\omega).\ S(\omega).e^{i\psi(\omega)}\,d\omega \qquad (3.9)$$

or, combining equations (3.8) and (3.9):

$$Y(t) = \frac{1}{2\pi}\int_{-\infty}^{\infty} A(\omega).\ S(\omega).e^{i[\psi(\omega)+\varphi(\omega)]}\,d\omega. \qquad (3.10)$$

It will be seen that Y(t) is again a sum of sinusoids, where the amplitude of each original sinusoid has been multiplied by a factor $A(\omega)$ and the phase has been shifted by an amount $\varphi(\omega)$.

The considerations in this section have indicated methods for determining the corrections for the frequency response of a measuring channel. Even after these corrections have been applied, <u>dynamic errors</u> from other sources may still be present. These may be due to non-linearities in the system, to inaccuracies in the determination of the dynamic response characteristics, etc.

The procedures described in this section can, in practical cases, often be simplified considerably by a proper choice of the dynamic characteristics of the measuring channel. From Figure 3.6 it can be seen that the amplitude response of a second-order measuring channel will be correct within 1 °/o if the bandwidth of the input signal does not exceed 20 °/o of the natural frequency and if the damping factor is 0.7. Similarly, an amplitude response which is correct within ± 5 °/o can be obtained from a channel which has a damping factor of 0.6 in the range of relative frequencies between 0 and 1. A sufficiently constant amplitude characteristic over the bandwidth of the input signal does not guarantee, however, that the input and output signals are similar to the required degree. It is often

forgotten that phase distortion can also occur. An extreme example of phase distortion is shown in Figure 3.9. In Figure a an input signal is given which is composed of 2 sinusoids with a frequency ratio of 3. Figure b gives a correct output signal, which only has a certain lag relative to the input signal. Figure c shows the output signal if the phase angle of the higher of the 2 frequencies has shifted by an extra 180°. It will be seen that the signal is distorted, though the amplitude response is correct at both frequencies. No phase distortion will occur if the phase angle varies linearly with frequency, as is the case in Figure 3.7 in the range of relative frequencies between 0 and 1 for a damping factor of 0.7. Then at all frequencies a constant time delay occurs, which is called the group delay. If the group delay at all frequencies is constant, no phase distortion will occur.

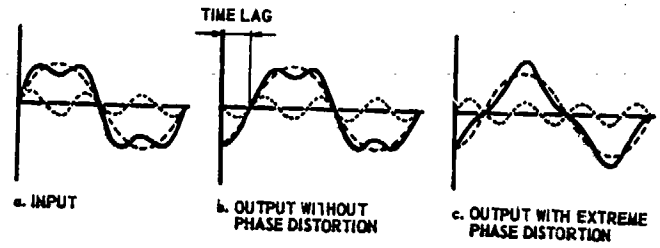


Figure 3.9 Phase distortion in a signal with frequency components f and 3f

In many cases the input signal consists of a frequency band which is of interest to the measurement and a frequency band which is not of interest to the measurement. This can occur, for instance, if accelerometers are used for the measurement of the motions of an aircraft (frequency band of interest, say 0 - 5 Hz). If the accelerometer is mounted to a part of the aircraft which vibrates at a frequency of, say 30 - 40 Hz, this vibration will also be measured by the accelerometer but is of no interest to the measurement of aircraft motion. If these frequency bands are sufficiently separated, the frequency response characteristics of the measuring chain can often be chosen so that the signal bandwidth which is of interest is reproduced without undue distortion while the amplitude of the unwanted part of the signal is reduced markedly. This will be discussed in more detail in the next 3 chapters.

3.9 FINESSE*)

When a measuring instrument is introduced in a physical environment, it introduces a change in this environment. The input to the instrument will, therefore, be different from the value which the measurand would have had if the instrument were not there. Examples of this effect are:

- a micrometer exerts a force on the object which it measures and thereby changes its dimensions
- an angular position indicator exerts a moment about the axis on which it is mounted and changes its position
- a temperature probe changes the calorific capacity of the object whose temperature is being measured and thereby changes its temperature
- a pressure probe (and its support) change the pressure distribution in a flowing medium; an extension of this is the static pressure error in aircraft: there the presence of the aircraft itself, together with that of the probe and its support, changes the pressure distribution
- a vibration pick-up will change the distribution of masses of the structure
- the loading caused by the input impedance of an electrical measuring system reduces the voltage to be measured. For servo systems the input impedance at balanced condition may be higher than the impedance in the transient condition.

These effects can influence both the static accuracy, as in the case of the micrometer and of the pressure probe, and the dynamic accuracy, as in the last two examples mentioned. If these errors are negligible, it is said that the finesse of the measuring system is high.

Errors due to low finesse can in some cases be corrected during data processing, together with the instrumental errors. Often this will, however, be difficult or even impossible, as for instance when a vibration pick-up changes the vibration of the structure. Then the measuring system must be chosen so that the finesse error will remain as low as possible (for instance by choosing a light vibration pick-up) and the probability distribution of the residual must be estimated.

---

*) See note on page 3.5

3.10 REFERENCES

1. Vocabulaire de métrologie légale, Organisation Internationale de Métrologie Légale, March 1969

2. Electrical transducer nomenclature and terminology, Instrument Society of America, Document no. ISA-537.1, Third edition, 1970

3. E.O. Doebelin — Measurement systems, application and design, Part I, McGraw Hill, 1966

4. G.M. Jenkins, D.C. Watts — Spectral analysis and its applications, Holden Day, 1969

CHAPTER 4
TRANSDUCERS
by
L.H. Weirather

4.1 INTRODUCTION

The first element of a measuring channel generally is the device used to convert the measurand, i.e. acceleration, temperature, etc., into a form which is more suitable for transmission or recording purposes. This device is called a transducer and most generally is designed either to provide an electrical output or, with a suitable mirror arrangement, to reflect a light beam onto a photographic recording medium. Another family of frequently used transducers consists of the mechanical direct-indicating instruments, with pointer or numeric indicators. In this family, the transducing and display functions are integrated into a single box, linked by mechanical elements.

The primary emphasis of this chapter will be placed on transducers with an electrical output, although many of the principles and characteristics discussed here apply also to other types of devices. A large variety of physical effects are used for producing the electrical outputs of transducers. The characteristics of these physical effects themselves will not be discussed in detail in this chapter. They are described in several of the references given in Section 4.4. This chapter will concentrate on those characteristics of transducers which are primarily relevant to their role as part of a measuring channel.

For most measurands there are several transducing principles in use. For instance, accelerations can be measured by transducers utilizing potentiometers or strain gages, by piezoelectric transducers, by force-balance transducers, etc. Each of these transducer types has different characteristics and different areas of application. The general characteristics of these transducing principles will be discussed in Section 4.3.

4.2 CHARACTERISTICS OF TRANSDUCERS

4.2.1 Introductory remarks

Transducer characteristics can be conveniently divided into three groups: input, transfer and output characteristics. These three groups will be separately discussed below. These characteristics mainly determine whether a transducer can be used for a particular measurement. In the final choice of the transducer other aspects, such as environmental conditions, cost, reliability, availability, maintenance and calibration requirements and applicability to other measurements also play an important role. These aspects are discussed in more detail in Chapter 2.
It must be stressed that, especially for relatively simple tests and for some special-purpose tests, the cost, accuracy and reliability of the complete instrumentation system may be largely determined by the choice of the transducers.

4.2.2 Input characteristics

The most important input characteristics are:

- the normal measuring range and the ranges of the environmental parameters (defined in Section 3.4) As the errors in many types of transducers are proportional to their range, generally the best accuracy will be obtained if the range of the instrument is equal to the range of the measurand or slightly larger.
- the finesse (defined in Section 3.9). This must be appropriate to the measurement, i.e., the effect of the transducer on the physical process being measured must be small with respect to the allowable total error.
- the cross-axis sensitivity. Many transducers which are nominally sensitive only to inputs along one axis of the instrument (such as accelerometers and rate gyroscopes) produce spurious outputs to an input perpendicular to its sensitive axis. An example of cross-axis sensitivity of an

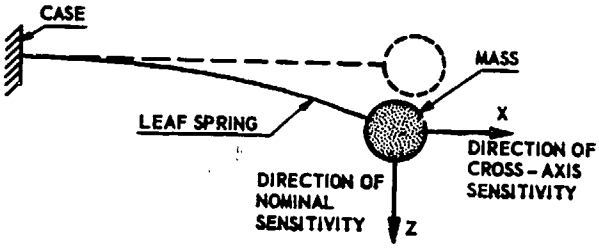


Figure 4.1 Cross-axis effects in an accelerometer with a leaf spring and mass

accelerometer is shown in Figure 4.1. The nominal axis of sensitivity is the Z-axis, which is perpendicular to the undeflected spring blade. If the spring is deflected by an inertial force acting on the mass along the Z-axis, the mass-spring system will also become sensitive to inertial forces along the X-axis. For the relatively small deflections which occur in accelerometers of the type shown in Figure 4.1, the cross-axis error is proportional to the product of the accelerations in the X and Z directions.

A similar relation exists for many other types of accelerometers and for most rate gyros. For some types of transducers, for instance piezo-electric transducers, the cross-axis error is not proportional to the product of the two inputs.

The cross-axis error is small if the total deflection is small, as in force-balance accelerometers. The cross-axis effect can often be reduced by a careful choice of the orientation of the instrument with respect to the aircraft. For the accelerometer of Figure 4.1 the effect of accelerations along the Y-axis will be much lower than the effect of those along the X-axis. The transducer should, therefore, be oriented so that the largest cross-axis accelerations act along the Y-axis. If the law which governs the cross-axis sensitivity is known and the other acceleration is measured separately, it is possible to apply a correction during data processing.

- error in the location or the alignment of the transducer. In many flight tests the location of the transducer relative to the center of gravity of the aircraft, and the alignment of the sensitive axis of the transducer relative to the reference axes of the aircraft must be known precisely. Any uncertainty will increase the errors in the measurement.

4.2.3 Transfer characteristics

The transfer characteristics define the relation between the magnitude of the input quantity and the magnitude of the output quantity of the transducer. They are determined from the static calibration, the dynamic response characteristics (amplitude and phase) and the associated error distributions. These are defined and described in Chapter 3. As already stated there, the transfer characteristics will in general change with the environmental conditions. Probably the most troublesome aspects of the environment are temperature, shock and vibration, and electromagnetic interference.

The main effects of temperature are zero and/or sensitivity shifts in the output. Some transducers may be compensated for temperature errors by using various electrical and mechanical techniques. Beyond about 250°C, temperature compensation becomes extremely difficult to design and implement. Various methods are used to protect transducers from extreme temperature variations. These include temperature-controlled compartments, air and liquid cooled enclosures, heat sinks, integral heaters and heater blankets. One of the most insidious, and little known, environmental effects is caused by temperature transients. These cause temperature gradients in the instruments which can produce temperature errors much larger than those which occur under (quasi-) static conditions in the same temperature range. It is practically impossible for the user to correct the effects of these temperature gradients. Their effect can only be reduced by isolating the transducer as well as possible from the temperature environment.

The effects of shock and vibration are especially difficult to eliminate for inertial transducers such as accelerometers and rate gyros, since they act upon the transducer in the same way as its regular input. For example, an accelerometer used to measure the motion of the center of gravity of an aircraft will also respond to vibrations of its mounting plate relative to the c.g. If the signal to be measured and the spurious vibration signal are in the same frequency band, it is impossible to separate them by filtering. If the noise frequency is markedly different from the frequencies of interest, there are 3 methods to reduce the spurious vibration signals:

- choosing a transducer with a frequency response which will transduce the signal of interest without distortion and which will be insensitive to the unwanted frequencies
- using a mechanical low-pass filter (vibration isolation mounts) between the source of the excitation and the transducer
- introducing an electrical filter in the output of the transducer.

In general, using a transducer with an optimal frequency response for the measurement is preferable to the other two methods mentioned. This will not always be possible. The problem with mechanical filters is that they often have a non-linear frequency response and will therefore distort the signal of interest. Reasonably linear vibration isolation mounts are available and are used in some inertial platforms. They are, however, costly and have to be specially designed for each transducer. In some cases good results have been obtained by mounting the inertial transducer on a relatively large wooden board, which provides a reasonably linear frequency response and more damping than most other construction materials. The use of electrical filters in the output of the transducer can lead to large errors if the amplitude of the vibration is so high that it drives the transducer outside its linear range. If the vibration frequency is much higher than the cut-off frequency of the filter but still within the bandwidth of the transducer, the fact that high-amplitude vibrations were present cannot even be seen from the filtered output. An example of this effect is described in Section 5.2.3 for the case where a closed-loop accelerometer is used to measure aircraft motions. These transducers are chosen because of their inherently high accuracy. They have, however, a bandwidth of the order of 0 to 200 Hz, though the frequency range of the signal of interest is of the order of 0 to 5 Hz. High-frequency vibrations of the mounting plate of the transducer may then saturate the servo amplifier and thereby cause large distortion. In this case the only way to reduce the errors is to reduce the amplitude of the high-frequency vibration sensed by the transducer. This can only be done by using a mechanical filter between the vibrating mounting plate and the transducer.

The effect of shock and vibration on non-inertial transducers can be suppressed by the same methods as mentioned above. Here, however, the most practical method is to use anti-vibration mounts. Transducers with small movable masses are generally less susceptible to vibration than others.

The detrimental effects of angular vibrations and especially angular accelerations on some transducers is frequently overlooked. Angular accelerations can for instance affect the accuracy of rate gyroscopes to a marked degree.

Transducers may be required to operate in the presence of strong electromagnetic fields. Generally speaking, transducers with low output impedance, high output voltage and short cable lengths are less susceptible to this type of interference. Other transducers can be used in this kind of an environment, but they must then have specially designed shielding and electrical ground circuits (Chapter 5).

Other environmental conditions such as pressure, humidity, sand and dust, salt spray and radiation may also have to be considered for specific applications.

4.2.4 Output characteristics

The output characteristics of a transducer are generally less important than the input and transfer characteristics since they can be appropriately and conveniently modified using signal conditioners (see Chapter 5). But even so, they are important in the design of the overall data collection system. The main output characteristics are the type of output, the output level and the output impedance.

The types of output can be divided into three general categories:
- analog outputs
- pulse outputs
- digital outputs.

Transducers with analog outputs comprise the largest class of transducers in use today. The output voltage is generally classed as being either DC or AC.
Transducers with DC output produce either a voltage, a current, a charge or an impedance which is a measure of the physical input signal to the transducer. As most recorders and most analog-to-

digital converters require DC input signals, some of these transducers can be directly connected to the recorder or encoding device without intervening signal conditioning. In many cases, however, signal conditioning is necessary because voltage amplification, or impedance matching, etc. is necessary (see Chapter 5). For transducers with an AC output the information is contained in either the amplitude, the phase or the frequency. For transducers with a phase output, a phase reference signal must be available which is often the AC supply voltage to the transducer. The AC output is usually converted into either a DC output or a pulse output before it is used to drive a recorder, telemetry transmitter or analog-to-digital converter.

The transducers with pulse output. The information is represented as a pulse rate, a pulse position or a pulse width. The signals in this category can be converted to digital form relatively easily.

The transducers with digital output produce coded output signals which are digital in nature. In some cases the coded signal is available at the output continuously and in others only when the transducer is interrogated by the recording device or telemetry system.

Besides the type of output, there are a number of other electrical output characteristics which are of importance for the matching of the transducer to the recording or telemetry system or for the design of the signal conditioning equipment (see also Chapter 5). The most important of these are:

- bandwidth
- output level
- output power
- output impedance
- ground connection.

The bandwidth of all components of the measuring channel should be at least as broad as the bandwidth of the transducer (with its output filter, if one is used). The output level usually is expressed in terms of the output voltage or current. The output voltages are roughly divided into high-level outputs, 0 to 5 volts or higher, and low-level outputs, usually 0 to 20 millivolts. Often different signal conditioning equipment is provided for high-level and low-level outputs. Even if the desired voltage or current is available, the output power that can be taken from the transducer may be insufficient so that power amplification is necessary in the signal conditioner.

It is generally desirable that the output impedance be low, not more than a few ohms. This is important because a low output impedance requires a lower power to obtain a certain value of the output voltage or output current, and because the circuit is less sensitive to many types of electrical interference. For those transducers which have a high output impedance (such as, for instance, the piezoelectric transducers), signal conditioning circuits may be necessary before the signal is transmitted over long wires.

Many transducers designed for flight testing have a floating output, so that grounding connections can be made at the most convenient point of the circuit. In other transducers one of the output terminals is connected to the power ground or via the transducer case to the aircraft structure on which it is mounted. In such cases special measures in the signal conditioning circuits are required (see Chapter 8).

4.3 TYPES OF TRANSDUCERS

A brief discussion will be given of the characteristics of the more common types of transducers. The main emphasis will be on the transfer and output characteristics because these are particularly important in the overall design of the data collection system. The input parameters and the transducing principles will only be mentioned insofar as they are of direct importance to the discussion.

Table 4.1 provides a listing of several types of transducers with ranges, accuracies, frequency responses and types of output typical of those used in many flight test programs. Many other types are available for special applications. It should be noted that variations in accuracy and other characteristics are possible within each category in the list.

In the following discussions the transducer types have been divided into five categories, each of which will be discussed separately. These are active analog, passive analog, pulse and frequency generating, digital and closed-loop.

TABLE 4.1 - TYPICAL TRANSDUCERS USED FOR FLIGHT TEST INSTRUMENTATION

MEASURAND	TRANSDUCER COMMON NAME	TRANSDUCTION PRINCIPLE	TYPICAL MAXIMUM RANGE	ACCURACY*)	DATA FREQUENCY RESPONSE (Hz)	OUTPUT Type		Level Low 1V High 1V	Impedance Low 10k High 10k	REMARKS
Acceleration and vibration	Accelerometer	Potentiometric Strain gage Piezoelectric Force balance	± 50g ± 100g ± 10.000g ± 35g	Medium Medium Medium High	20 200 10,000 20	DC,AC DC,AC AC DC	Voltage Voltage Volt,charge Current	High Low Low/High High	Low Low See remark Low	Must be used with charge amplifiers or with preamplifiers with very high input impedance
Accustics and sound	Microphone	Capacitive Piezoelectric	180 dB 160 dB	Medium Low/medium	100,000 10,000	AC AC	Voltage Volt,charge	Low Low/High	High	
Air flow direction	Vanes Aerodynamic probe	Potentiometric Synchro Diff.pressure	± 30° ± 30° ± 30°	Medium Medium Medium	10 10	DC,AC DC	Voltage Voltage	High High (See pressure)	Low Low	
Attitude	Gyroscope	Gyroscopic	± 45°	Medium	10-100	(See displacement)				
Attitude rate	Gyroscope	Gyroscopic	± 2000°/sec	Medium	10-100	(See displacement)				
Displacement, linear	Potentiometer LVDT	Potentiometric Diff.transfmr.	300 mm 300 mm	Medium Medium	20 20	DC,AC AC	Voltage Volt,phase	High High	Low Low	
Displacement, angular	Potentiometer Synchro Shaft encoder	Potentiometric Inductive	3600° 360° 360°	Medium High High	20 20 20	DC,AC AC Digital	Voltage Voltage	High High	Low Low	
Flow rate,vol Flow rate,mass	Flow meter	Turbine	3.000 gal/hr 20,000 lbs/hr	Medium		Pulse rate		Low	Low	
Strain,loads	Strain gage	Resistive	6,000 μ in/in	Low	10,000	DC,AC	Voltage	Low	Low	
Liquid level		Capacitive Nuclear	12 ft 6 ft	Medium Medium		AC Pulse	Voltage	Low	High	
Pressure	Pressure transducer	Potentiometric Strain gage Capacitive Piezoelectric	500 psi;350 N/cm² 5,000 psi;3500 N/cm² 1000 psi;700 N/cm² 10,000 psi;7000 N/cm²	Medium Medium Med/High Medium	20 10,000 100,000 10,000	DC,AC DC,AC AC AC	Voltage Voltage Voltage Volt,charge	Low Low Low Low/High	Low Low High See remark	See remark acceleration and vibration
Rotary speed	Tacho generator	Inductive	100 °/o RPM	Medium		Frequency		Low	Low	
Temperature	Resis.thermom. Thermistor Thermocouple	Resistive Resistive Thermoelectric	1000°C 300°C 1200°C	High High Medium	20 200 2	DC,AC DC,AC DC	Voltage Voltage Voltage	Low/High Low/High Low	Low Low Low	

* Low accuracy: error > 3 °/o FS, medium accuracy: error < 1-3 °/o FS, high accuracy: error < 1 °/o FS.

4.3.1 Active analog transducers

Active or self-generating transducers require no external source of power or excitation. The most common types of active analog transducers used in flight test applications are piezoelectric, thermoelectric, magnetoelectric, and photoelectric transducers.

Piezoelectric transducers (Fig. 4.2) operate on the principle that a voltage is generated in certain crystal materials when they are subjected to mechanical forces or stresses along specific planes. Figure 4.2a shows a section through a transducer where the acceleration produces a shear force in the piezoelectric material; in Figure 4.2b it produces a compression. Piezoelectric transducers are basically charge generating devices with an output impedance of several hundreds of Megohms. When used as voltage generators, they must be connected with very short cables to special high-impedance voltage amplifiers. The calibration has to be done after installation, since small variations in the capacitance of the cable could cause significant changes in the calibration. The use of charge amplifiers (see Chapter 5) minimizes the effects of cable capacitance, noise, etc.

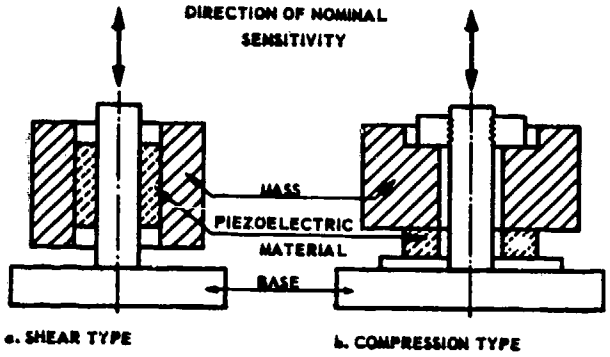


Figure 4.2 Two types of piezoelectric acceleration transducers

The outstanding characteristics of piezoelectric transducers are their large range (up to 10,000 g) and extremely high natural frequency (about 30,000 Hz), and their small size and weight. They are used extensively for the measurement of high-frequency vibrations, but do not respond to low-frequency vibrations. The low-frequency cut-off point of these devices is 10 Hz or somewhat lower, depending on the preamplifier used.

Thermoelectric transducers. (Fig. 4.3) The thermoelectric effect is utilized in thermocouples, which consist of two dissimilar metal wires whose ends are connected together. When the junctions are subjected to different temperatures, an emf is produced. The magnitude of the emf depends upon the temperature difference and the materials of the conductors. The most common types of thermocouples used in flight testing are copper-constantan, chromel-alumel, iron-constantan and platinum-platinum/rhodium.

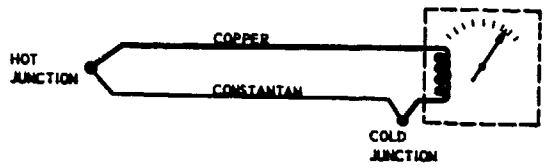


Figure 4.3 Copper-constantan thermocouple circuit

Thermocouples are mainly used for the measurement of high temperatures, for example, in engines. The output voltage is in the range of 0 to about 60 mV and typical aircraft installations have an output resistance of a few ohms. Thermocouples require either a reference temperature device for maintaining a constant temperature at the cold junction, or a mechanical or an electrical compensation for cold-junction temperature changes. Special bonded-foil thermocouples are used for measuring surface temperatures.

Magnetoelectric transducers. These are instruments of the induction generator type, in which motions of a conductor or coil in a permanent magnetic field induce a voltage in the coil. The output voltage is proportional to the magnetic field strength, the number of turns in the coil and the velocity of the coil relative to the field. Common applications of this effect are the AC and the DC tachometers used in measuring rotary velocity. The magnetoelectric effect is also used for generating pulses (see Section 4.3.3).

Photoelectric transducers. These produce a voltage which is roughly proportional to the light energy falling on a photoelectrical cell and are mainly used for on-off type measurements, such as

digital shaft encoders.

4.3.2. Passive analog transducers

The physical input varies the impedance or impedances in these transducers. An external power source is required for producing an output voltage or current. In many of these transducers two or three output voltages are produced, the ratio of which contains the information (potentiometers, differential transformers, synchros). Other types, which have only a single variable impedance (resistance thermometers, variable self-inductances, variable capacitances), are often used in bridge circuits or in variable-frequency oscillators.

4.3.2.1 Variable resistance transducers

Potentiometers. The value of the output of a potentiometer is determined by the mechanical rotation or the linear displacement of a sliding contact. The resistance element usually consists of a wire wound around a form, or a metallic, carbon or conductive plastic film deposited on a non-conducting base. The resolution of wire-wound potentiometers is limited by the number of wires used; the resolution of film potentiometers is unlimited.

Potentiometers are extensively used in flight testing. Their main advantage is that they can give high-level DC outputs which can be easily filtered and which can be used without amplification. Potentiometers must, however, be applied with care because they can be subject to a number of problems:

- There is always friction between the resistance material and the wiper. Though this friction can be quite small for high quality potentiometers, it limits the attainable accuracy in cases where only small forces are available, as in low-range pressure transducers.
- Vibrations and accelerations can affect the contact pressure of the wiper resulting in output failures. This can sometimes be reduced by choosing the best orientation for the potentiometer with respect to the main direction of the vibration.
- Wear of the resistance element can be a problem, especially if the wiper moves in the same region for a long time. Wear can cause non-linearities before a final break-down occurs.
- Film type potentiometers can have a non-linear characteristic near the end of their range and near taps and can sometimes accept only a very small wiper current.

Potentiometers are used for the direct measurement of linear and angular displacement. They are also used in transducers to measure displacements derived from physical input quantities such as pressure, acceleration, force, and rate gyro deflection.

A special type of potentiometer is used in the so-called "DC synchronous system" (such as "Desynn"). The 28 V DC supply is connected to two wipers, which move over a circular potentiometer with three taps. The voltages between these taps can be transmitted over long wires. The ratios of these voltages determine the position of the pointer in a special indicator. It should be noted, that the electrical output of the potentiometer is less suitable for recording purposes.

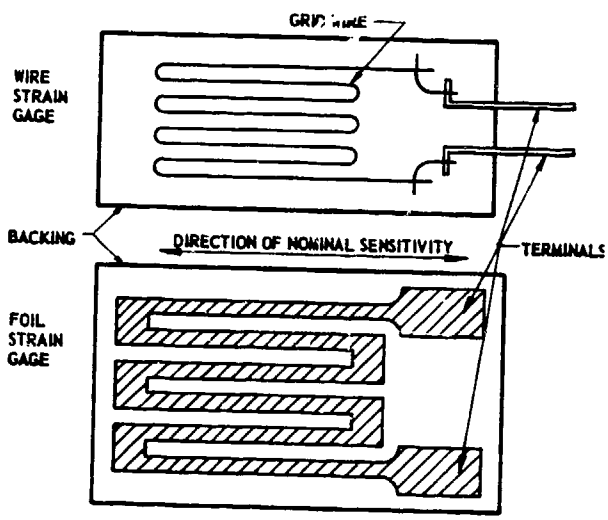


Figure 4.4 Foil and wire strain gages

Strain gages. The wire strain gage and the foil strain gage are based on the principle that the resistance of a wire or foil changes in a reproducible way when stretched within their elastic limits. Two types of strain gages are used extensively in flight testing:

- bonded-wire or foil strain gages (Fig. 4.4). The wire or foil is bonded to a thin sheet of backing material, which in turn is cemented to the structure to be tested. In order to optimize the sensitivity of the gage for

particular applications, the sensitive element can be formed in different patterns. For example, the strain gages shown in Figure 4.4 measure strains in a single direction. Other types of strain gages (rosette types) are available for measuring omni-directional strains. These consist of several strain gages of the type of Figure 4.4 bonded to the same base, at predetermined angles with respect to each other. For measuring membrane deflections gages of spiral shape are sometimes used. Bonded strain gages are used by themselves as transducers for measuring strains in structures, and are also incorporated in the design of other types of transducers (i.e. pressure gages).

- unbonded wire strain gages. (Fig. 4.5). In many transducers a type of strain gage is used in which the wires are wound under tension between small poles mounted on the transducer elements. These transducers are somewhat more stable than those using bonded strain gages because of the absence of the backing material and the bonding film.

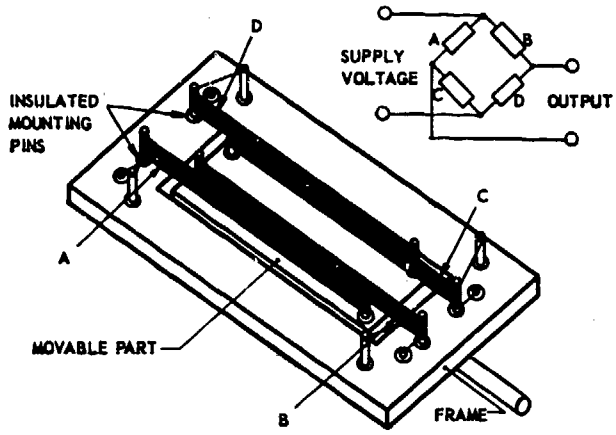


Figure 4.5 Displacement transducer with four unbonded strain gages

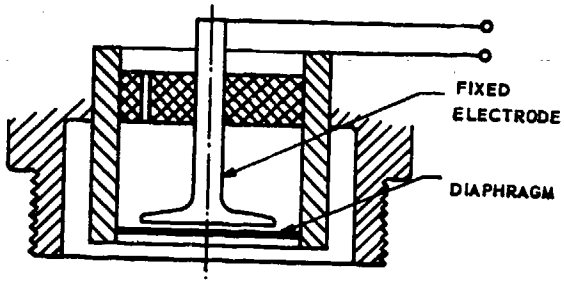
Strain gages are primarily used in Wheatstone bridge circuits. One, two or all four arms of the bridge can be made up of strain gages. The strain gages should be so arranged that temperature effects are reduced. The bridge supply can be either DC or AC. The bridge output is low-level, usually with a maximum of about 100 mV.

A relatively new development is the semiconductor strain gage, which operates on the piezoresistive effect. The gage material is a single crystal of doped silicon. The principal advantage of this type of strain gage is its high sensitivity: over 50 times greater than for the wire type. Its temperature sensitivity is, however, much larger than in metal strain gages, so there is often little gain in using them when temperature can change considerably. They are used in transducers, where effective means for temperature compensation can be incorporated during manufacture.

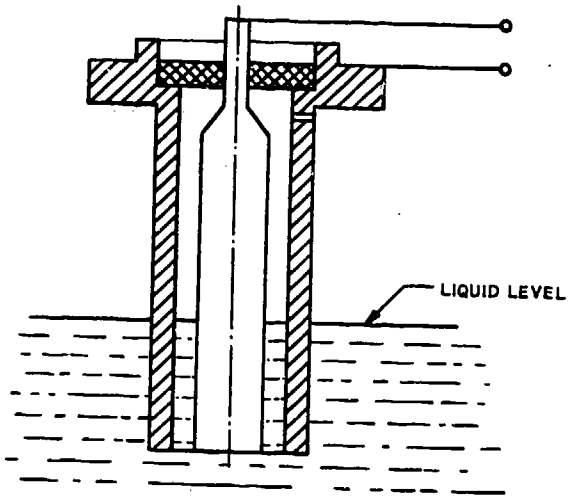
Resistance thermometers. Two types of resistance thermometers are widely used in flight testing: the metal wire resistance thermometer and the thermistor.

The metal resistance thermometers are usually made of nickel or platinum wire. The reproducibility is very good and the calibration is nearly linear over a wide temperature range. Some types can be used to temperatures of 1500°C. There are two basic configurations: the bulb type and the surface type. The standard bulb types have a metal protection tube around the wire; they are relatively large and have a slow response. Special types, for instance those used in many stagnation temperature probes, are somewhat smaller and have their wire directly exposed to the air. In those types, time constants of a few seconds can be attained. The output voltage is generally larger than for strain gages, and can often be used without amplification. When designing measuring circuits for resistance temperature elements, the maximum allowable self-heating of the element must be taken into account. Elements for measuring surface temperatures consist of a fine wire grid bonded to a backing material and are similar in construction to strain gages. They are cemented to the surface where the temperature measurement is to be made.

Thermistors incorporate a resistance element made of a semiconductor material. They can be made very small in size, thus allowing a relatively high frequency response. Many types have a negative temperature coefficient. The relation between resistance and temperature usually is non-linear.



a. CAPACITIVE PRESSURE TRANSDUCER



b. CAPACITIVE FUEL LEVEL TRANSDUCER

Figure 4.6 Capacitive transducers

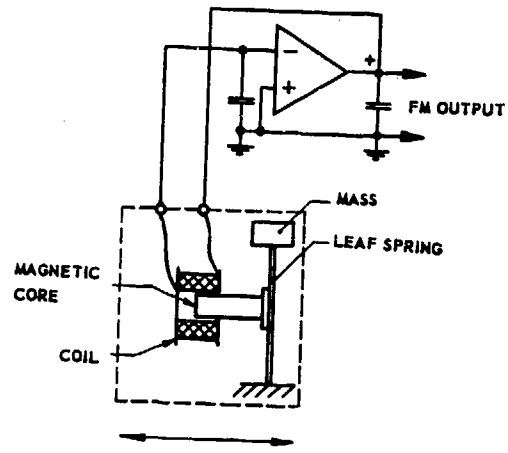
4.3.2.3 Variable inductance transducers (Fig. 4.7)

In variable self-inductance transducers the position of a core in a coil determines the self-inductance of the coil. Inductance type transducers are available for a large number of inputs which produce a linear displacement, such as pressure, acceleration, force, etc. They are low-impedance devices which produce relatively high output signals. They are often used for analog FM recording or telemetry. The coil in these applications forms part of the oscillator circuit which produces the frequency-modulated signal (Fig. 4.7a). They are also used in bridge circuits. Figure 4.7.b shows a bridge circuit with two self-inductances one of which increases while the other decreases with the measurand. These transducers can be made very small, and can operate at relatively high temperatures.

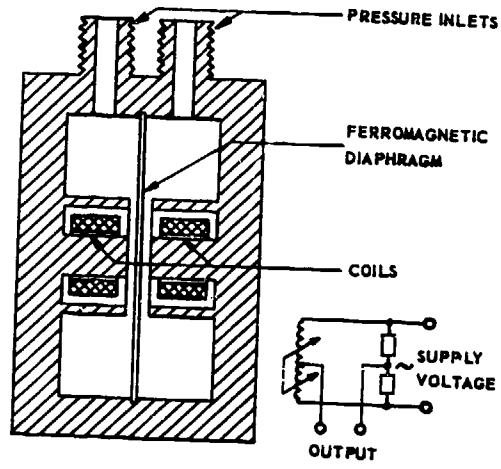
4.3.2.2 Variable capacitance transducers (Fig. 4.6)

In variable capacitance transducers the effective area of two parallel plates, the separation between them and the dielectric strength of the material separating them, determine the capacitance. Common examples of transducers using a change of plate spacing are the condensor microphone and the capacitive pressure transducer (Fig. 4.6.a). Variation in the dielectric is generally used to measure fuel level (Fig. 4.6.b).

Advantages of capacitive transducers include the small size, excellent high-frequency response and ability to withstand high temperatures. Disadvantages include the temperature sensitivity and the high-impedance output, which requires rather complex signal conditioning circuitry.



a. VARIABLE SELF-INDUCTANCE ACCELERATION TRANSDUCER IN AN OSCILLATOR CIRCUIT



b. VARIABLE SELF-INDUCTANCE PRESSURE TRANSDUCER IN A BRIDGE CIRCUIT

Figure 4.7 Inductive transducers

4.3.2.4 Variable differential transformers

In a variable differential transformer the mutual inductance between coils is varied. The most common type of linear variable differential transformer (LVDT) consists of a hollow concentric non-magnetic form with three windings: one primary and two secondary. A pictorial diagram of an LVDT is shown in Figure 4.8. The position of a magnetic core or armature within the coil determines the relative mutual coupling between the primary and secondary windings. When an AC voltage is applied to the primary winding, and the two secondary windings are connected in series opposition, the net output is the difference of the two secondary voltages which is directly proportional to the core displacement.

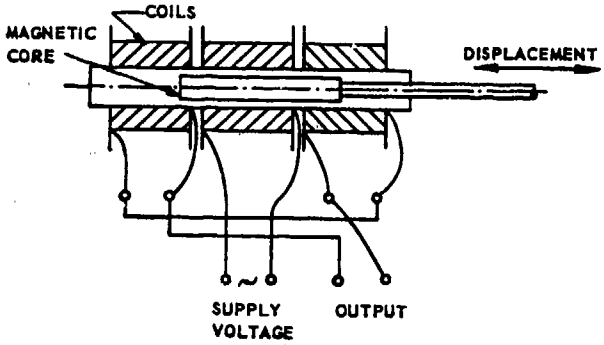


Figure 4.8 Linear variable differential transformer

Differential transformers are simple in construction, durable, provide frictionless core motion, and are capable of operation in relatively high temperature environments. The output can be of the order of several volts, with a low impedance which simplifies cable requirements. Rotary models of the differential transformer are also available.

4.3.2.5 Synchros

Generally, synchros are used for positioning by electrical means the shaft in a repeater to the same angular position as another shaft on which the transmitter is mounted. In their normal use the output is, therefore, an angular position of a rotor, not an electrical output. As such they are used in flight testing for the transmission of angular positions to pointer instruments. But their main importance in flight testing is in a different application. Since synchros are extensively used in the normal operational equipment of the aircraft, many measurements can be obtained by tapping the electrical signal of these operational circuits, thereby precluding the need to install separate transducers. Rather complex signal conditioning circuits are required (see Chapter 5), but nevertheless this method is often more convenient than the use of additional transducers.

There are two general classes of synchros: the torque type and the control type. In torque synchro circuits (Fig. 4.9a) the rotors of the torque transmitter and the torque receiver are both connected to the AC supply voltage (in aircraft applications usually 26 Volt, 400 Hz.). If the two rotors are not aligned, a current will be generated in the stator circuit which moves the torque receiver rotor to its correct position. The positioning accuracy of the receiver under static conditions is about 0.25 degrees (i.e. better than 0.1 % of the 360 degree full scale value). Due to the relatively low power, the large inertia of the torque-receiver rotor and the slip-ring friction in the receiver, the frequency response is rather poor. An electrical measurement of the transmitter position can be obtained by tapping the stator wires using high-impedance circuits. The rotor voltage is used as a reference in some signal conditioners.

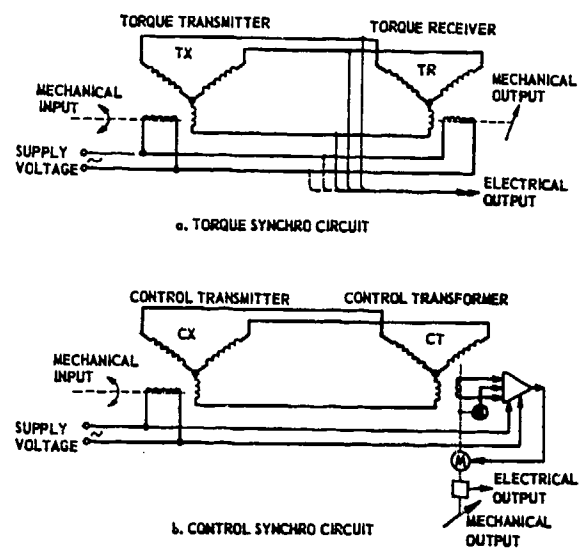


Figure 4.9 Synchro circuits

In control synchro circuits (Fig. 4.9b) only the rotor of the control transmitter is connected to the supply voltage. Currents in the stator circuit induce a voltage in the rotor of a control transformer which is amplified and fed to a servo motor which drives the control-transformer rotor to its correct position. The accuracy of the alignment of the rotor can be of the order of 0.05 degrees and the dynamic response can be much better than for torque synchros. The output of the synchro chain is, as with torque synchros, a shaft position. If an electrical output of a control synchro chain is required, this can be taken from the stator wires as in Figure 4.9a. It is, however, better and more accurate to mount an electrical transducer (e.g. a potentiometer or a digital shaft encoder) on the axis of the servo motor and to use the output of this transducer.

A number of special synchro types have been developed:

- differential synchros. These are control transmitters which have a three-winding rotor as well as a three-winding stator. The rotor is connected to the stator of a normal control transmitter. The control transformer connected to the stator will then be positioned to indicate the sum or the difference of the angular positions of the shafts of the control transmitter and of the differential transmitter.
- brushless synchros. In these synchros the excitation of the rotor is done by inductive means, instead of by sliding contacts. This provides a modest improvement in both accuracy and dynamic response.
- synchros with fixed coils ("synchrotel"). In these synchros the "rotor winding" does not move, but is wound on the same core as the stator windings. The coupling between the "rotor winding" and the stator windings is controlled by a small and light moving piece of metal. As this coupling is much less efficient, they require more supply power and are usually excited by 115 Volts, 400 Hz. The inertia and the friction of the rotor can be made so low that these synchros can be used in sensitive altimeters and similar instruments to provide an electrical connection to a control transformer.

In a few cases resolvers are used in flight testing. These are similar to synchros, but have only two stator coils, which produce AC voltages proportional to the sine and cosine of the angular position of the rotor. They are, for example, used in many inertial platforms. The stator voltages can be tapped in the same way as for synchros.

4.3.3 Pulse and frequency generating transducers

For pulse-generating transducers the information is represented as a continuously variable pulse repetition rate. Frequency generating transducers produce a (more or less) sinusoidal output with a frequency proportional to the value of the input to the transducer. In the majority of flight test applications this frequency is transformed in the signal conditioning circuit to a pulse rate by amplification and clipping. Although frequency outputs can be used in other ways, for example in analog telemetry and recording circuits or in eddy-current type tachometers, in flight test applications they are generally transformed into a train of pulses. They are, therefore, described here under the same heading. Pulse and frequency generating transducers are analog transducers, but their output can be very easily transformed into a digital output using a counter. They are, therefore, sometimes classified as semi-digital transducers.

4.3.3.1 Pulse-generating transducers

Most pulse-generating transducers produce a series of voltage or current pulses whose rate is proportional to the value of the physical parameter measured. The most common types operate upon the magnetoelectric or the photoelectric principles.

The magnetoelectric sensor consists of a coil with a small permanent magnet. If the field of the magnet is disturbed momentarily by the movement of a piece of ferro-magnetic material passing it, a pulse is generated in the coil. This principle is often used for the measurement of rotation speeds

in engines and in turbine-type flow-rate transducers (Fig. 4.10). For each revolution one or more pulses are induced in the sensor.

The photoelectric or photoresistive sensors are also used for detecting rates of rotation. The pulses are produced by periodically interrupting a light beam from a lamp to a photoelectric cell or a photoresistance. This principle is not often used in flight testing. One application is in tape recorders to detect whether or not the tape is running.

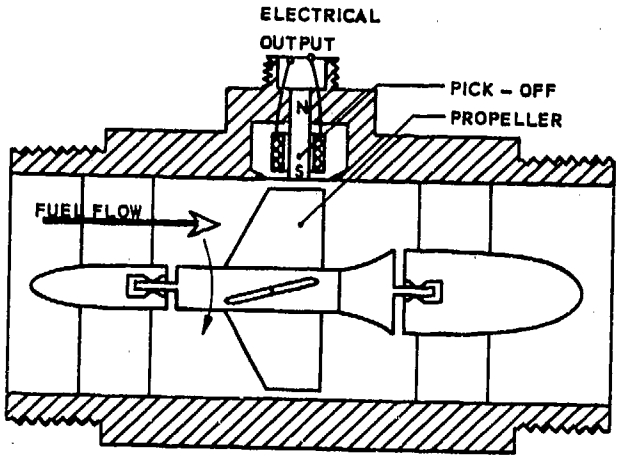


Figure 4.10 Pulse-generating fuel flow transducer

4.3.3.2 Frequency-generating transducers

Many types of frequency-generating transducers are used in flight testing. One is the AC tachometer, which has an output proportional in both frequency and amplitude to the angular velocity of the shaft to which it is attached. Other types of frequency-generating transducers include the variable self-inductance transducers and the capacitive transducers when used as an element in a variable-frequency oscillator. In a fourth type, the vibrating-wire transducer, the measurand changes the tension of a vibrating wire, and thereby its vibration frequency. Part of the output signal is fed back through a servo amplifier to maintain the oscillation. The same principle is also used for tuning forks and crystals which are used in timers. Here, however, the frequency is maintained as constant as possible.

4.3.4 Digital transducers

The digital transducers produce a digitally coded output. The most common type of digital transducer uses a shaft-position encoder such as shown in Figure 4.11. The same principle is also employed in linear-scale encoders, which can be used to encode rectilinear motions. The digital encoders may be grouped into two major categories: the brush and the brushless types.

Figure 4.11 shows a brush-type encoder. The disk is composed of a series of conducting and non-conducting areas on several concentric rings, one ring for each bit in the output. The conductive areas are all connected to a voltage source and a digital "1" is produced by the current which flows through a brush when it contacts a conducting area. No current flows through the brush when it is in contact with a non-conducting area and the digital bit produced is "0".

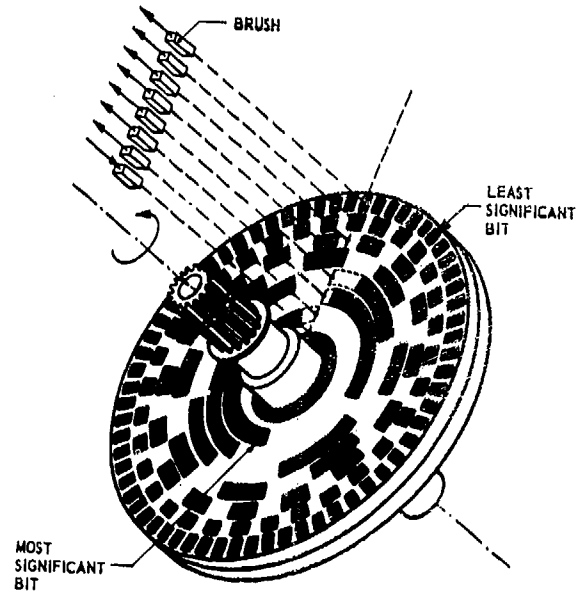


Figure 4.11 Seven-bit brush-type digital shaft-position encoder

The brush-type encoders are rather sensitive to vibration, which may affect the contact between the brushes and the disk. This effect is somewhat less in brushless encoders. The disks are similar in layout, but the detection of a "1" is done by a magnetic, capacitive or optical sensor.

There are also some digital transducers which are analog transducers with a built-in electronic digitizer, functioning on the same principle as the analog-to-digital converters described in Chapter 5.

Digital transducers are not used extensively in flight testing at the present time, because the effects of vibration have not been completely overcome at least for the encoder-types, and because problems still exist with high-frequency response. Another reason is that digital transducers are very costly and are only available for a limited number of transducer types. Since analog-to-digital converters must be provided for the transducers which have only analog outputs, it is generally more economical to avoid using the few transducers which do have digital outputs. If in the future more types of digital transducers become available, this situation may change.

4.3.5 Closed-loop transducers

In closed-loop transducers, also called feedback transducers or servo transducer , a portion of the output is returned to the input either electrically or mechanically. This feedback signal opposes the input signal and is therefore called "negative feedback". The effect of the feedback loop is to increase the accuracy of the transducer over that of comparable open-loop transducers. In many cases, accuracies of 10^{-4} of full scale or better can be achieved in closed-loop transducers. When such accuracies are required in flight testing, for instance in pressure transducers for measuring altitude and for acceleration transducers for measuring aircraft motions, closed-loop transducers are extensively used. Two types of closed-loop transducers are used in flight testing, viz. force-balance transducers and closed-loop position tranducers.

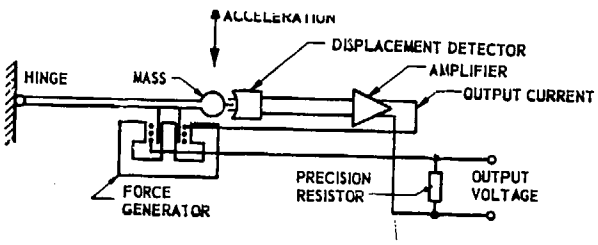


Figure 4.12 Force-balance acceleration transducer

The majority of closed-loop tranducers used in flight testing are force-balance transducers. The principle is shown in Figure 4.12. The physical input (an acceleration in Figure 4.12) exerts a force on a sensing element. In open-loop transducers this force would be balanced by a spring and the deflection of the sensing element would be measured. In a closed-loop transducer an electrical signal from the displacement detector is sent via an amplifier to an electrical force generator which repositions the sensing element. The current required to drive the repositioning device to equilibrium is a measure of the physical input quantity and is the output of the transducer. It can be converted to a voltage by means of a precision resistance. Although a finite deflection of the sensing element is required in order to obtain an output from the displacement detector, this deflection is much smaller than for equivalent open-loop transducers.

In closed-loop position transducers the physical input is not a force but a displacement. In these instruments the servo amplifier is used to reposition the displacement detector until its output is zero. An example of such a position servo has been described in Section 4.3.2.5, which is the system used for control synchros (Figure 4.9b). A similar servo system is used in some closed-loop pressure transducers.

The advantages of closed-loop transducers can be summarized as follows:

- environmental factors have much less effect on the accuracy because it is a null-seeking device
- the static accuracy can be much higher because friction effects are practically eliminated
- dynamic linearity can be increased because of the absence of friction effects and of non-linear effects in mechanical damping devices
- the dynamic characteristics are stable because they mainly depend on the electrical characteristics of the feedback loop
- the sensing element travels only a minute distance before equilibrium is attained. Therefore, cross-axis sensitivity is much less than in equivalent open-loop transducers.

The disadvantages are mainly that they are more costly and larger in size and weight than conventional transducers and that overloading may cause very large errors. A characteristic which can be a disadvantage under some circumstances is that the bandwidth generally increases with increasing accuracy. This can cause problems when a low-frequency signal must be measured in the presence of high-amplitude, high-frequency noise (see Section 4.2.2).

4.4 REFERENCES

1. W.P. Mason — Electro-Mechanical Transducers and Wave-Filters, Van Nostrand, N.Y., 2nd ed. 1948
2. H. Nyquist — The Regeneration Theory, Bell System Tech.Journal (1932)
3. W.G. Cady — Piezoelectricity, McGraw Hill, 1946
4. E.O. Doebelin — Measurement Systems, Application and Design, McGraw Hill, N.Y., 1966
5. H.K.P. Neubert — Instrument Transducers - An Introduction to Their Performance and Design, Oxford-Clarendon Press, 1963
6. George J. Thaler — Elements of Servo-Mechanism Theory, McGraw Hill, N.Y.
7. G.F. Harvey (Ed.) — ISA Transducer Compendium, 2nd Edition, Parts 1, 2, 3, Plenum Press, 1969, 1970, 1972
8. Instrument Society of America, Standards and Practices for Instrumentation, Third Edition, 1970, Document No. ISA-537.
9. M.B. Stout — Basic Electrical Measurements, Second Edition, Prentice-Hall, Inc., N.J., 1960
10. T.G. Beckwith, N.L. Buck — Mechanical Measurements, Addison-Welsley Pub. Co., Mass. 1961
11. H. Chelner — Aerospace Instrumentation Design and Application, ISA Conference on Advances in Instrumentation, Philadelphia, Penn. 1970
12. H.N. Norton — Handbook of transducers for electronic measuring systems, Prentice-Hall Inc, 1969

CHAPTER 5
SIGNAL CONDITIONING

by

W.G. James

5.1 INTRODUCTION

The output signal from a transducer is usually modified several times before it is in the final form in which it can be subjected to computation. Examples of such modifying operations are amplification, filtering, sampling, digitizing, data compression, digital format conversion, modulation on a carrier frequency, application of calibrations, etc. In principle, these operations do not change the essential information contained in the signal. Each operation is done in order to adapt the signal to the input requirements of the next unit in the measuring chain. In a broad sense all operations between the transducer and the computer which is used for the final analysis could be regarded as signal conditioning. In flight test instrumentation language the expression "signal conditioning" is generally reserved to indicate the modifying operations done on board the aircraft. It is used to indicate the signal modifications between the transducer and the input stage of the recording or telemetry system, the indicator or the airborne computer (Fig. 5.1). What is meant by these latter expressions depends very much on the general layout of the system and on how the different circuits have been divided between the "boxes". For instance, a "digital tape recording system" can be regarded as consisting of:

- the recorder deck only; then the write amplifiers, analog-to-digital converters, etc., will be regarded as signal conditioners
- the recorder deck with the (built-in) write amplifiers; in that case the write amplifiers will not be called signal conditioners but will be part of the recording system
- a system of recorder and electronics accepting standard DC and digital input signals, the components of which need not even be all housed in the same box; in that case the commutators, analog-to-digital converters and write amplifiers will be included in the digital recording system. The term signal conditioner will then be applied only to those circuits which convert the analog transducer outputs to the standard DC signals and the digital transducer outputs to the standard digital input format required by the system.

In this chapter the notion "signal conditioning" will be used as follows. For single indicators and for photo-panel recorders all circuits outside the indicator houses are regarded as signal conditioners. Continuous-trace recording systems are considered to consist of the recorder box only. Tape recording systems will consist of the tape deck and the write amplifiers which are usually housed in it. Similarly, telemetry systems will include the transmitter. All circuits between the transducer and these systems will be included in the functional notion of signal conditioning and will be described in this chapter. Recording systems will be discussed in Chapter 9, telemetry systems in Chapter 10.

In a few cases, operations like filtering are done on the physical input signal before it enters the transducers. This is usually also called signal conditioning as illustrated in Figure 5.1.

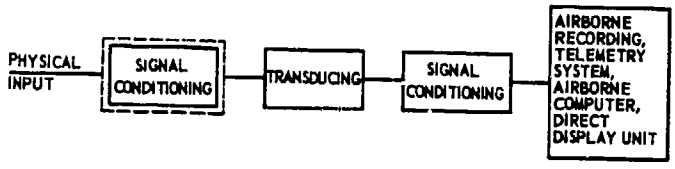


Figure 5.1 Block diagram showing the function of signal conditioning in an airborne flight test instrumentation system

The main reasons for signal conditioning are:

- The transducers can be selected on the basis of availibility or of optimal transducing quality, without additional requirements on their output characteristics (see also Chapter 4).
- Transducers from the operational systems on the aircraft can also be used for flight test purposes. Conditioning circuits must then be made to ensure that the flight test system can under no circumstances interfere with the safe execution of the flight.
- If the frequency range of the transducer output is too large to be handled correctly by the recording of telemetry system, signal conditioning can reduce the bandwidth of the signal by eliminating

frequency ranges which are of no interest for the measurements.

- Conditioning circuits can protect the signal against extraneous signals induced by the environment and reduce the effect on the signal of changes in the environment.
- The calibration of a transducer changes if more than an insignificant part of the available power is transferred by the output signal. Signal conditioning amplifiers reduce the power taken from the transducer.

Signal conditioning also includes transformations of the transducer output signal. As explained in Chapter 4, normally these output signals are:

- DC analog (very low frequency or quasi-static)
- AC analog (including some special types like variable impedance and synchro outputs),
- frequency and pulse rate,
- digital.

The commonly encountered signal transformations are shown in Table 5.1.

Table 5.1 Frequently used signal conditioning operations

Conversion from	Conversion to			
	DC	AC	Digital	Frequency
DC	Amplification	Amplitude modulation	A/D conversion	Frequency modulation
AC	Demodulation	Amplification	Via DC	---
Impedance	Bridges	Bridges	---	Frequency modulation
Frequency	Demodulation	---	Counting	
Synchros	Special purpose conversions			---

They can be divided into two groups:

Linear operations, i.e. operations where the input and output signals are of the same type and in which the relation between output and input can be described by a linear differential equation, and signal conversions, where the input and output signals also are in some way linearly related, but are of different types.

5.2 LINEAR OPERATIONS ON SIGNALS

5.2.1 Theoretical introduction

The linear operations can be divided into four groups:

- Amplification and attenuation. The main object of these operations is to increase or to decrease the voltage, current, power or impedance level of the signal. In general, the spectral distribution will also be affected slightly.
- Filtering. Here the objective is to change the spectral distribution of the signal. Small changes in the wanted signal components unintentionally also occur.
- Zero shifting. This generally involves the addition of a constant voltage or current to the signal.
- Compensation. The objective of this operation is to reduce the response to undesired variables by means of subtraction from the perturbed signal of a similarly perturbed auxiliary signal. This technique is applied, for instance, in bridge circuits and in differential amplifiers.

The linear operations can be described by a transfer function as discussed in Chapter 3. At each radial frequency ω the output $Y(\omega)$ is related to the input $X(\omega)$ by the relation

$$Y(\omega) = A(\omega).e^{i\varphi(\omega)}.X(\omega) + N(\omega) \qquad (5.1)$$

where $A(\omega)$ is the amplification factor, $\varphi(\omega)$ is the phase angle between input and output and $N(\omega)$ is the zero shift and the amplifier noise.

For amplifiers ($A>1$) and attenuators ($A<1$) the amplification factor and the zero shift are usually independent of frequency within the bandwidth of the amplifier, and the phase shift is either zero

$$Y = A.X + N \tag{5.2}$$

or 180 degrees (inverting amplifier)

$$Y = -A.X + N \tag{5.3}$$

In most conditioning circuits the term N can be ignored.

When designing linear signal conditioning circuits, especially filters, it must be kept in mind that the transducers and the signal converters (such as analog-to-digital converters) also have a transfer function. When considering the overall frequency response of a measuring chain all these "filtering effects" must be taken into account. Sampling devices modify the frequency response (aliasing); this effect is discussed in detail in Chapter 6. The frequency response can be displayed by the amplitude and phase characteristics as discussed in Chapter 3. For some applications it is easier to use the power spectral density curves, which give the relation between the square of $A(\omega)$ and ω.

5.2.2 Amplification and attenuation

The signal conditioning operations of this type usually do not significantly affect the spectral content of the signal, so that they can be described by equations (5.2) or (5.3). The object of such operations is one or more of the following signal modifications:

- to change the voltage or current level to adapt the signal to the input requirements of the recording or telemetry unit,
- to increase the power of the measuring signal,
- to match the impedance of the transducer (which may be very high) to that of the recording or telemetry system (which can be low),
- to recover a small signal which is the difference of two high voltages,
- to isolate electronic circuits from others, so that a failure in the isolated part will not affect the functioning of the remaining circuit.

Attenuation. Commonly used attenuation circuits for the reduction of high-level signals are the potentiometer and the step attenuator (Figure 5.2). Protective isolation can be obtained by using a series resistance (Figure 5.3). It should be noted that such attenuator circuits dissipate power, so that the signal power level is reduced. Especially in the case of protective attenuation it may be necessary to provide a power amplifier in order to maintain sufficient signal power.

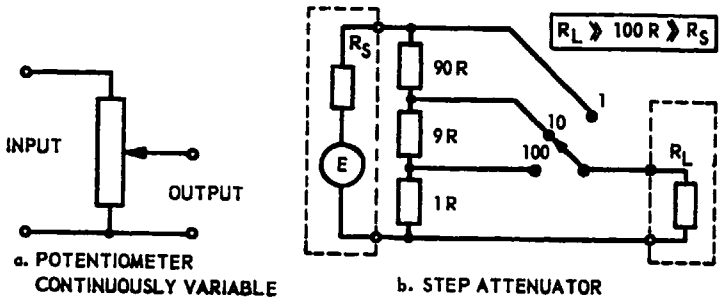


Figure 5.2 Variable resistive attenuation

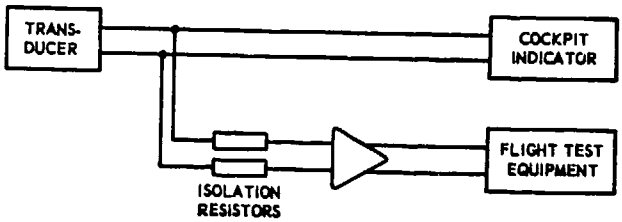


Figure 5.3 Resistive isolation of the flight test instrumentation input when transducers from the cockpit system are used

Amplifiers come in many different types. A first classification is: voltage amplifiers, current amplifiers and power amplifiers.

A second classification involves the frequency response of the amplifiers. A DC amplifier can accomodate signals with a spectral content ranging from zero to some upper cut-off frequency, which can be quite high. The passband of an AC amplifier is limited at the lower frequency side of the spectrum by a cut-off frequency above zero; it will not pass DC. AC amplifiers are used when a low frequency response is either not required or undesirable, for example in AC servo's, carrier systems, synchro links and vibration measurements. The application and use of DC amplifiers generally requires more design effort because of the problems associated with contact potentials, offset voltages and currents, drift and temperature compensation;

however, they must be used if a frequency response down to very low frequency is required.

Amplifiers can also be classified according to the degree of electric isolation between the input and output terminals (Figure 5.4).

Single-ended amplifiers are essentially three-terminal devices: input and output have one (ground) terminal in common. In simple single-ended amplifiers the common terminal is directly connected to the amplifier case and via this case to the aircraft structure (Fig. 5.4a). In that case the signal will be directly influenced by differences in potential between the points where the transducer, the amplifier and the next stage of the electronic circuit are connected to the aircraft structure (ground loops). It is, therefore, often better to use a floating single-ended amplifier, in which the common signal input and output terminal is isolated from the amplifier case (Fig. 5.4b).

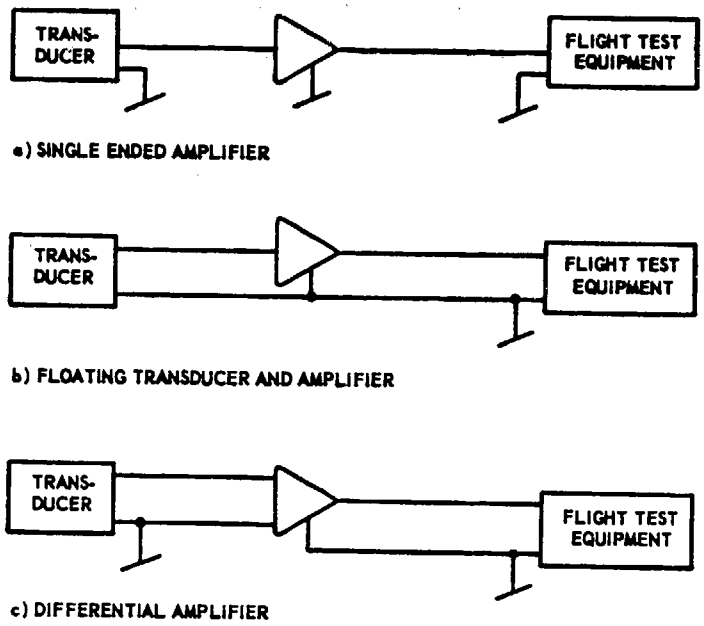


Figure 5.4 Types of amplifier input circuits

Then a signal return wire must be added, because the signal cannot return through the aircraft structure. If, as is usually the case for modern instruments, the output terminals of the transducer and the input terminals of the next circuit are also isolated from the aircraft structure, the signal return wire can be grounded to the structure at the most convenient point. In differential amplifiers the input and output sides have no common terminal (Fig. 5.4c). They are, in principle, a combination of two amplifiers with a common input ground, interconnected so that the output is the amplified difference between the two "hot" input terminals. The amplification function of a differential amplifier is

$$Y = A_1X_1 - A_2X_2 \qquad (5.4)$$

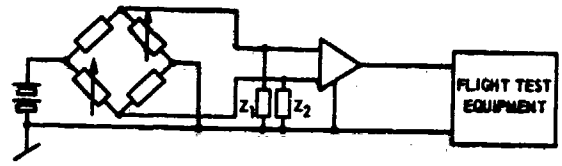
where Y is the output voltage, X_1 and X_2 are the input voltages referred to the common input ground and A_1 and $-A_2$ are the amplification factors of the two "halves" of the amplifier, one of which is inverted with respect to the other. Great care is taken in the construction to make these two amplification factors exactly equal. Then

$$Y = A(X_1 - X_2) \qquad (5.5)$$

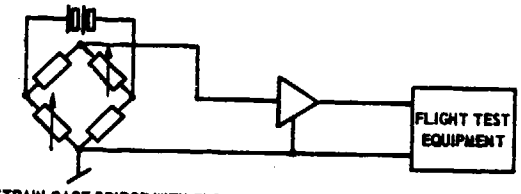
which means that the amplifier produces indeed an output which is proportional to the difference between the two input voltages, regardless of the voltage level of these two inputs with respect to ground. One limitation is that the input voltages X_1 and X_2 with respect to ground should not be so high that the input circuitry would fail. This limit is of the order of 10 Volts for ordinary differential amplifiers. If the input voltages are higher than this limit a floating or true differential amplifier must be used, in which there is no galvanic connection between the signal and the power ground of the amplifier.

The main advantage of the differential amplifier over the single-ended amplifier is, that it only amplifies the "normal mode" voltage $(X_1 - X_2)$ between the two signal lines and is insensitive to the "common mode" voltage $\frac{1}{2}(X_1 + X_2)$ with respect to (signal) ground. An application of this common mode rejection characteristic of the differential amplifier is shown in Figure 5.5a. The low level bridge output signal is at a DC potential of half the bridge supply voltage with

respect to the common ground of the battery and the amplifier. Yet the amplifier will only amplify the bridge output signal voltage. This measurement could also have been made with a single-ended amplifier, if the bridge power source were floating with respect to ground (Figure 5.5b). This latter configuration is often inconvenient, especially if several bridges have to be connected to the same input by way of a commutator. The common mode rejection characteristics of a differential amplifier will also eliminate the effect of some types of noise pickup.



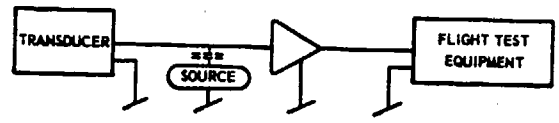
a) STRAIN GAGE BRIDGE WITH GROUNDED SUPPLY AND DIFFERENTIAL AMPLIFIER



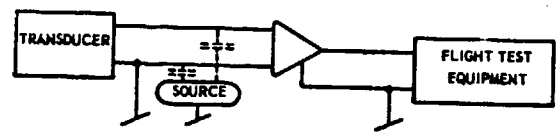
b) STRAIN GAGE BRIDGE WITH FLOATING SUPPLY AND SINGLE-ENDED AMPLIFIER

Figure 5.5 Methods for eliminating common mode effects in strain gage bridges

In Figure 5.6a the effect of capacitive noise pickup on the input wire of a single-ended amplifier is illustrated. The noise voltage will be added to the signal voltage. In Figure 5.6b the noise pickup on the two input wires appears as a common-mode voltage at both input terminals of the differential amplifier and will not be amplified. It is essential that the two input wires are very near to each other and that the circuits connected to the two input terminals are symmetric. In practice, the common-mode rejection of an amplifier is never perfect, because the amplification factors of the two sides are not equal. Thus the amplifier output will be affected by the common mode voltage, although the common-mode sensitivity will be much less than the normal-mode sensitivity. The ratio between these two sensitivities is called the <u>common mode rejection ratio</u>. It can vary between 10^{-2} (-40 dB) for a low quality integrated circuit to 10^{-8} (-160 dB) for a sophisticated instrumentation amplifier. However, the common-mode rejection of the complete circuit does not depend only on the amplifier characteristics. If the amplifier input impedances Z_i in the circuit of Figure 5.5a are not exactly matched, the common mode rejection ratio of the circuit will be appreciably lower than that of the amplifier. The common mode rejection ratio depends on the frequency of the noise (e.g. -160 dB at DC and -120 dB at 400 Hz).



a) CAPACITIVE NOISE PICKUP ACTING ON A SINGLE ENDED AMPLIFIER CIRCUIT



b) CAPACITIVE NOISE PICKUP ACTING ON A DIFFERENTIAL AMPLIFIER CIRCUIT

Figure 5.6 The effect of capacitive noise on the input lines of single-ended and differential amplifiers

A type of amplifier which is often used in flight test instrumentation circuits is the <u>operational amplifier</u> (Fig. 5.7), which is available in many different types and qualities. It is a differential amplifier with a high input impedance (>200 kΩ), a high amplification factor (>50,000), a reasonably high common-mode rejection ratio (-80 dB) and a low output impedance (a few ohms). Operational amplifiers are manufactured in large quantities and are relatively cheap. They are, therefore, also often used in circuits which could be made with single-ended amplifiers. Figure 5.7 shows a few applications.

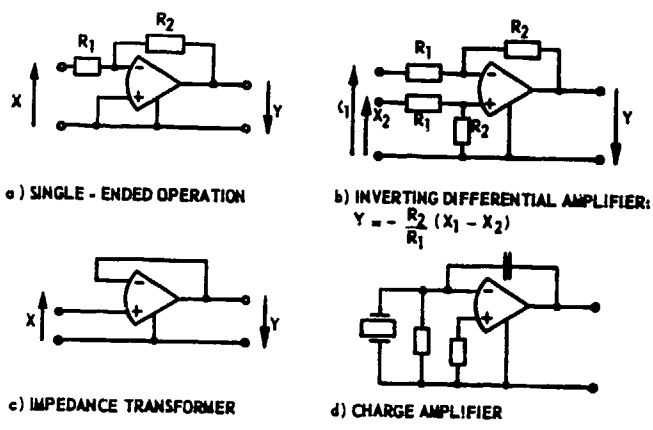


Figure 5.7 Circuits with operational amplifiers

The principle of operation will be briefly

described using Figure 5.7a, which shows an inverting amplifier in single-ended operation. One of the input terminals is directly connected to the grounded signal return line. The ratio between the output voltage -Y and the input voltage X is much less than the amplification factor of the operational amplifier. The voltage at the upper input of the operational amplifier must, therefore, be almost zero. This is achieved by means of the feedback resistor R_2. Due to the high input resistance of the operational amplifier the only current path is through R_1 and R_2, so the signal current through R_1 and the feedback current through R_2 must be equal. The amplification factor of the complete circuit -Y/X is then mainly determined by the ratio R_2/R_1 of two stable resistors and not by the amplifier characteristics. Figure 5.7b shows an inverting differential amplifier which in essence consists of two circuits of the same type; the symmetry of this circuit provides a better provision against interference and makes it possible to amplify a small voltage difference in the presence of a large common mode voltage. The circuit of Figure 5.7c is used to connect a high-impedance transducer to a measuring circuit with low impedance. The charge amplifier of Figure 5.7d is used with piezo-electric transducers as mentioned in Chapter 4.

A disadvantage of the DC amplifiers is that the output voltage can assume a value different from zero when the input voltage is zero (zero offset). Therefore, DC amplifiers are always equipped with a zero-offset adjustment which must be set when the amplifier has been connected in the circuit. Even if the zero offset was well adjusted initially, gradual changes in the amplifier (such as component ageing and temperature effects) will produce drift. Special DC amplifiers have been developed for use in low level circuits, which have an exceptionally low drift. An example is the "chopper" amplifier (Fig. 5.8). A mechanical or electronic chopper converts the DC into AC, which is then amplified in an AC amplifier. The high-level AC is then synchronously demodulated to a pulsating DC output and subsequently smoothed by a filter. Chopper amplifiers are available with high gain and extremely low drift, but the frequency range is limited to 10% or less of the chopper frequency because of aliasing effects (see Chapter 6). The frequency usually is 400 Hz for mechanical choppers, but electronic choppers have been developed which function at 100 kHz and higher. Recent developments in solid-state DC differential amplifiers have, however, reduced the need for such complicated devices.

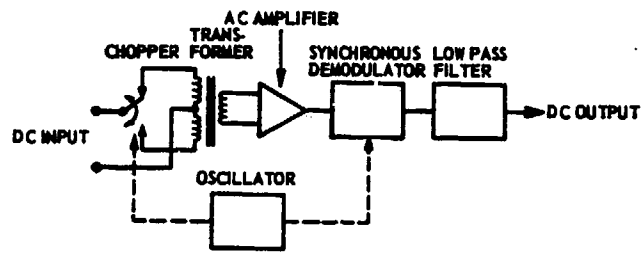


Figure 5.8 Chopper amplifier

A very important aspect in the design of every amplifier input circuit is the reduction of spurious input signals. Even very small spurious signals can have a significant effect on a low-level input to an amplifier. Several measures have already been briefly mentioned on the previous pages. Elimination of ground loops and the proper choice of ground connections is very important. The effectiveness of differential amplifiers in rejecting stray pickup from electric or magnetic fields will only be realized if the input circuits are symmetric and if the two input wires are very near to each other everywhere. Further improvements can be obtained by using shielded or twisted wires and by keeping low-level input wires far away from sources of spurious signals. These measures are discussed in some more detail in Chapter 8.

5.2.3 Filtering

Filtering is done if the signal contains components which are of no interest to the measurement and which have frequencies which are sufficiently different from those of the signal of interest to make filtering possible without significant distortion of the measuring signal. There are three main reasons for applying filtering to a measuring signal:

1. to attenuate the amplitudes of those signal components which are of no interest to the measurement and which may saturate transducers or other parts of the measuring circuit,
2. to filter out noise and high-frequency components of the signal which are of no interest to the measurement in order to reduce aliasing errors in case of sampling,
3. to present the signal so that it can be easily interpreted.

These applications of filtering will be explained by an example. An acceleration transducer is used to measure aircraft longitudinal accelerations which are in a frequency range between 0 and 5 Hz with maximum amplitudes of ± 0.4 g. In order to obtain sufficient accuracy a feed-back acceleration transducer is chosen with a range of ± 0.5 g and a frequency range from 0 to 100 Hz; the transducer will be saturated if the signal becomes larger than ± 1 g and then the output signal becomes unrelated to the input signal. Besides the signal of interest there are two spurious inputs:

- a resonance of the structural member on which the transducer is mounted, with an amplitude of 1.5 g at a frequency of 30 Hz,
- a 400 Hz signal picked up from the power supply of the aircraft by the input wires to the amplifier; the amplitude of this signal is equivalent to 0.2 g.

The spectral distribution of the input signals is shown in Figure 5.9. The first step must be to provide a filter to reduce the vibration input to the accelerometer to 0.5 g or less because otherwise the output of the transducer will be distorted. This must be done by means of a mechanical filter which actually reduces the 30 Hz acceleration of the transducer without distorting the frequency range between 0 and 5 Hz. Such a filter is relatively difficult to make; the only alternative is, however, to use a transducer with a linear range of ± 2 g or more, with a resultant loss in measuring accuracy. The second of the three filter functions mentioned above will become important if the signal must be sampled, for instance at 100 or 200 samples per second. Then the 400 Hz signal would be aliased to near 0 Hz (see Chapter 6) and would distort the low-frequency part of the spectrum which is of primary interest to the measurement. Therefore, an electric filter must be added to reduce the amplitude of the 400 Hz signal to an insignificant value. After these two filters have been applied the signal can be recorded. The third type of filter mentioned above is used to reduce the remaining noise to a level where it does not obscure the shape of plotted results or where it does not interfere with further computer processing (e.g. differentiation).

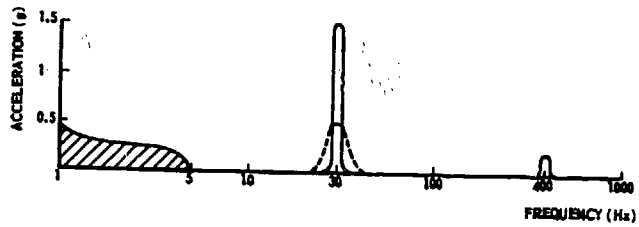


Figure 5.9 Example of a transducer output affected by noise

Filters are also extensively used in signal conditioners to reject by-products of some signal processing techniques, for instance in chopper amplifiers. One example is shown in Figure 5.8: after demodulation the chopper frequency components which are present in the signal must be filtered out. Similar applications occur in several types of modulators. Filters may also be used to correct the frequency characteristics of transducers.

There are several types of filters (see Figure 5.10 and Reference 1). The most important filter for flight test applications is the low-pass filter, which passes all frequencies below a certain frequency (cut-off frequency) and attenuates the frequencies beyond the cut-off frequency. The high-pass filter does the opposite: it attenuates all frequencies below the cut-off frequency and passes those beyond. Band-pass filters and band-stop filters are used in some applications. The filter also affects the phase relations in the pass band.

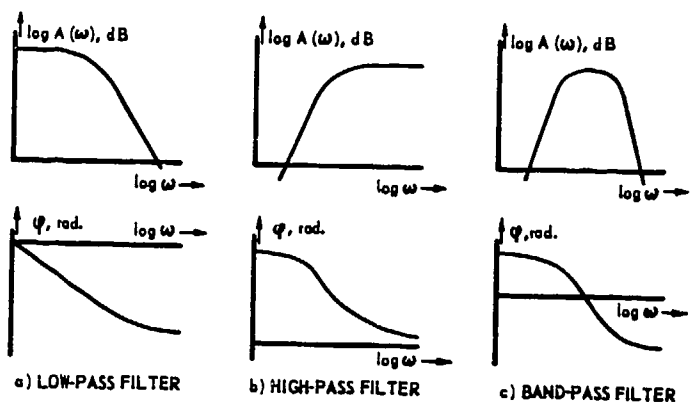


Figure 5.10 Gain (upper) and phase (lower) plots of typical filter types.

For each type of filter there are a number of parameters which can be varied: the order of the filter, the attenuation and the phase characteristics, the cut-off frequencies, the design principle of the filter (such as Tchebycheff, Butterworth, Gauss and linear phase filters). A careful analysis

of the exact characteristics is required before a filter can be chosen for a certain application. A somewhat more detailed discussion of this aspect is given in Chapter 6.

Both passive and active filters can be used in flight testing (Fig. 5.11). Passive filters are constructed using only passive elements, i.e. capacitors, resistors and inductors. Active filters use amplifiers in addition to passive elements. In general, the same filter characteristics can be obtained by active and by passive filters. The main advantage of active filters is, that they are physically smaller, especially if the break frequency is low. Additional advantages are that there is no loss in signal power and that the input and output impedance can be better matched to the other impedances in the circuit. The main disadvantages of active filters are that their output is not exactly zero for a zero input, that some noise is added to the signal and that a power supply is required.

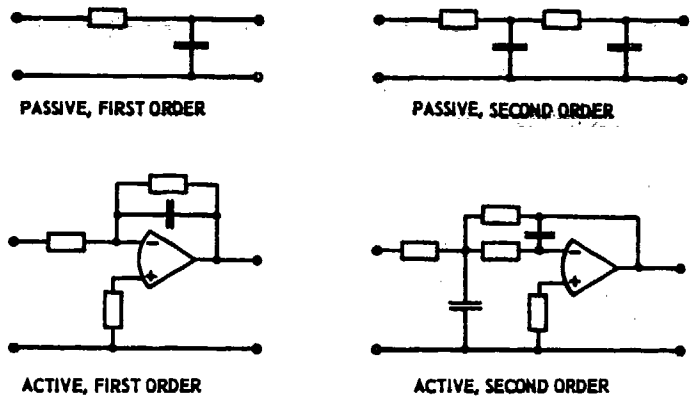


Figure 5.11 Examples of passive and active filters

5.2.4 Zero shifting

In some measurements full-scale output must be obtained from only a part of the total measuring range of the transducer. If the information content of a transducer output is between zero and a specific voltage, full-scale output can be obtained by suitable amplification. If the required range does not contain the transducer zero output, zero shifting (also called zero suppression) is applied by adding an offset voltage to the signal voltage, as shown in Figure 5.12. A typical circuit is shown in Figure 5.13. Similar circuits can also be used for AC transducer outputs, but then the phase relationship between the signal voltage and the offset voltage must be controlled.

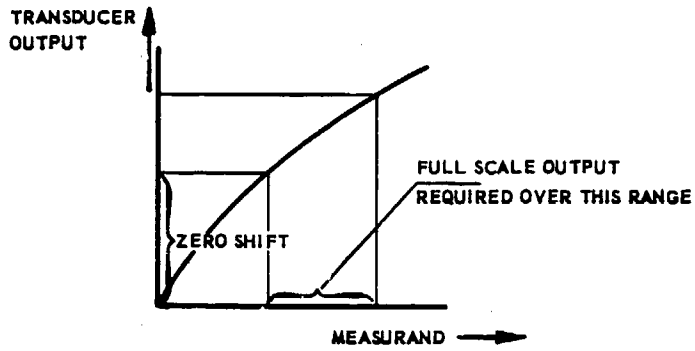


Figure 5.12 The principle of zero shifting

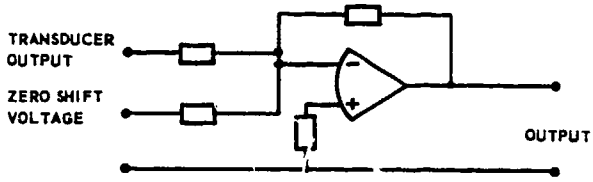


Figure 5.13 Summing amplifier applied in a zero shifting circuit

5.2.5 Compensation

A good example of the compensation principle is the bridge circuit, such as applied for resistance strain gages and variable inductance or variable capacitance transducers. The change in impedance usually is very small with respect to the nominal impedance of the transducer: for strain gages it is usually less than 0.1% of the nominal resistance of the gage. Such small changes can be accurately measured in bridge circuits. For resistive transducers the Wheatstone bridge is generally used (Fig. 5.14). The actual bridge consists usually of 4 resistors of the same nominal value. The

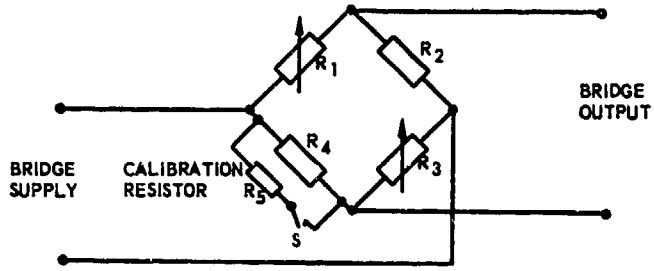


Figure 5.14 Wheatstone bridge with two active strain gages and calibration circuit

resistance of one, two or four of the bridge resistors depends linearly on the value of the measurand; these are called the active bridge elements. The other resistors, the passive bridge elements, are the compensation elements. All bridge elements must be mounted at the measuring point so that they are subjected to the same temperature environment. Thus the effect of temperature on the resistors is cancelled. Usually a calibration resistor is connected in parallel to one of the passive bridge arms. When the calibration switch is closed, the bridge output will change by a constant amount, independent of the instantaneous resistance values of the active gages. This makes it possible to check the calibration factor of the bridge circuitry during flight and, if necessary, to supply corrective data for data processing. The bridge supply voltage can be DC or AC. If the bridge supply voltage is grounded, a differential amplifier is required. Some examples are shown in Figure 5.5.

Bridge circuits are also used with capacitive and inductive transducers. An example of a variable-inductance transducer bridge is shown in Figure 5.15. This transducer consists of two coils and a movable core. When the core changes position the self inductance L_1 of one coil increases and the self inductance L_2 of the other coil decreases. One half of the bridge consists of the two coils with their internal resistances R_1 and R_2, the other half of the two fixed resistances R_3 and R_4. Balancing potentiometers are also shown. These are necessary for the adjustment of the resistive and the reactive balance of the bridge. The output signal is amplified by a feedback differential amplifier.

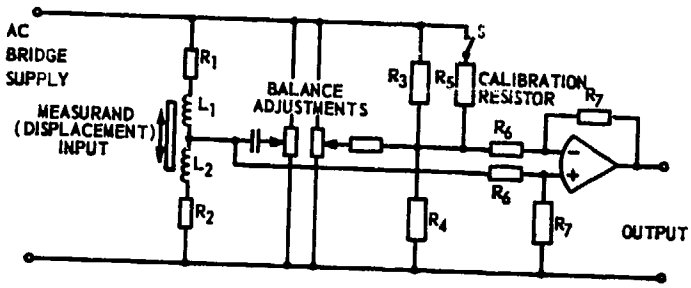


Figure 5.15 AC bridge circuit for use with a differential variable inductance transducer

A special group of bridge circuits are the servo-compensating bridges. The wiper of the balancing potentiometer in this case is activated through servocontrol: the output of the amplifier energizes a motor mechanically connected to the wiper of the balancing potentiometer, which minimizes the output signal of the bridge. The angle over which the potentiometer is rotated is then an accurate measure for the bridge unbalance and thus for the value of the measurand.

5.3 SIGNAL CONVERSION

5.3.1 General aspects

Signal conversions are those signal conditioning operations in which the signal type is changed. The most important signal conversions in flight test instrumentation are (see also Table 5.1):

- modulation
- demodulation
- analog-to-digital conversion
- special-purpose conversions, (e.g. synchros, resolvers).

5.3.2 Modulation

Modulation is the conversion of a signal to an alternating voltage or to a pulse train. The most important modulation techniques are (Ref. 1):

- amplitude modulation (AM)
- frequency modulation (FM)
- pulse duration modulation (PDM)
- pulse code modulation (PCM).

Amplitude modulation (AM) is the technique wherein the amplitude of a periodic wave with constant frequency (the carrier) is varied proportionally to the amplitude of the modulating signal. The information of the modulating signal is then contained in the amplitude of the modulated signal. Amplitude modulation on radio frequency carriers is used in low accuracy telemetry systems (see Chapter 10).

Frequency modulation (FM). The modulating signal controls the instantaneous frequency of a periodic

wave with constant amplitude (the carrier). Frequency modulation is used extensively in magnetic tape recording and in telemetry (see Chapters 9 and 10). It is also applied when the signal must be transported via a link which has unfavourable amplitude characteristics. This can be the case in electrically noisy environments, when sliprings or rotating transformers are present or when size and weight constraints preclude circuitry of the quality necessary for high quality signal handling.

For the generation of FM signals, a popular technique is to choose a suitable variable impedance transducer. Its impedance is part of a resonant circuit, which determines the frequency of the oscillator. The variable impedance may be an inductor, a capacitor or a resistor. Figure 5.16 shows an oscillator with a variable self-inductance transducer.
If the input signal is a DC voltage a Voltage Controlled Oscillator (VCO) can be used as an FM modulator.

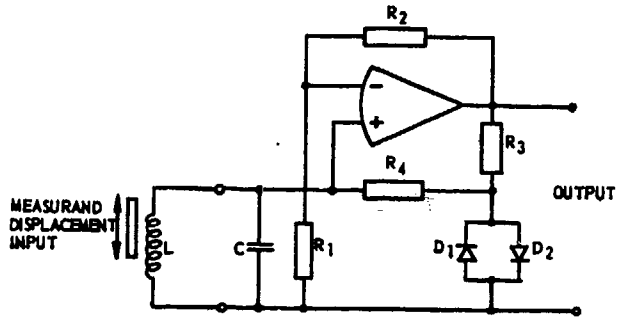
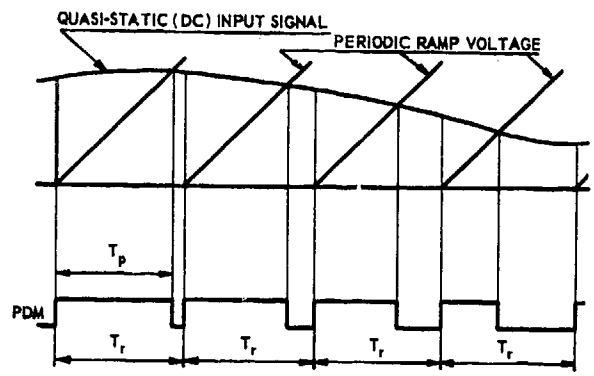


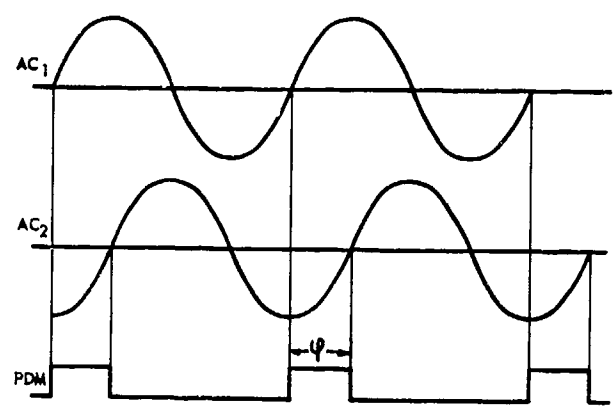
Figure 5.16 Frequency modulation by a variable inductance transducer

There are several types of analog pulse modulation methods, the most common of which is Pulse Duration Modulation (PDM). It produces a sampled signal; at regular time intervals T_r a pulse is generated, its pulse duration T_p being proportional to the magnitude of the modulation signal (Fig. 5.17). The information is contained in the ratio T_p/T_r. PDM is used in conditioning functions such as multiplication and phase-to-DC converters. In PAM-PDM multipliers one input signal amplitude-modulates a periodic pulse signal, the other input signal causing PDM. Consequently, the area of the resulting pulses is proportional to the product of the input signals.
A quasi-static output is obtained by averaging the pulses in a low pass filter.

The technique of pulse duration modulation of a quasi-static input is shown in Figure 5.17a. Simultaneously with the positive pulse front at the beginning of each period T_r an electronic ramp generator is started which produces a voltage that increases with time at a constant rate. The input signal is compared with the ramp signal and the output pulse is ended at the moment that the two have equal magnitude. Figure 5.17b shows a circuit for the conversion of the phase between two AC voltages into a PDM signal. The gate which produces the pulse is opened by a positive zero crossing of AC_1 and closed by a positive zero crossing of AC_2. This circuit is,



a) PDM METHOD FOR QUASI-STATIC INPUT SIGNAL



b) PDM METHOD USING THE PHASE DIFFERENCE BETWEEN TWO AC INPUTS

Figure 5.17 Pulse duration modulation (PDM)

for instance, used in a popular method for the conversion of synchro outputs to DC. It is then preceded by the circuit of Figure 5.18. This circuit converts the three output voltages of the synchro stator to a single voltage AC_1 of constant amplitude which has a phase shift with respect to the rotor supply voltage that is proportional to the input angle φ of the synchro rotor. This circuit consists of a precision transformer, which amplifies the difference between the voltages over two of the three stator windings with a factor $\sqrt{3}$, and an RC circuit which shift the phase of this voltage by 90 degrees before adding it to the voltage from the third stator winding. The phase angle of the voltage AC_1 with respect to the rotor supply voltage AC_2 is then converted into a PDM signal by the circuit of Figure 5.17b. This PDM signal can, if necessary, be converted to a DC signal proportional to the rotor angle φ by passing it through a low-pass filter. Detailed descriptions of this circuit are given in the literature, for instance in Reference 2.

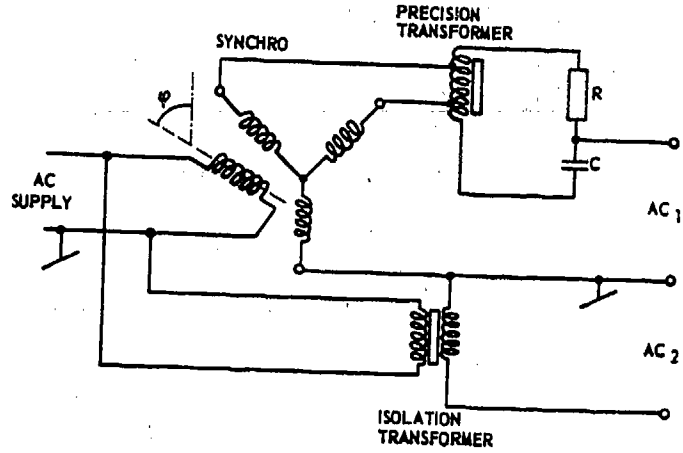


Figure 5.18 Synchro-to-phase converter

PDM modulation techniques have been extensively used in flight test instrumentation systems during the last decade. They are now more and more being superseded by digital techniques.

Pulse code modulation (PCM) also uses a sampled signal, but the information content of the samples is not in analog form as in PDM but it is quantized (digitized). During each interval T_r a series of pulses is produced which represent the value of the input sample in coded form. Several different encoding techniques are available, some of which are briefly discussed in Section 5.3.5 and in Chapter 10.

A new conversion technique has evolved from recent advances in opto-electronic technology. The ease of operation and the wide bandwidth of components such as Light Emitting Diodes (LED's) and silicon photo detectors, coupled with the increased reliability of glassfibre "cables" make the use of light as a carrier very attractive. The main advantage is that perfect electrical isolation can be maintained between modulator and demodulator and that the glassfibre conductor is not sensitive to electromagnetic interference.

5.3.3 Demodulation

A modulated signal can be restored to its original form or to an unmodulated signal of another type by demodulation. The demodulation of an amplitude modulated signal is usually done by a rectification process in which momentaneous carrier values of one polarity are passed unchanged, while carrier values of opposite polarity are inverted. A simple demodulation circuit is shown in Figure 5.19. The AM signal is rectified in a diode bridge circuit and then smoothed by a low-pass filter. If the range of the output signal must include both positive and negative voltages, a phase-sensitive demodulator must be used. The phase of the AM carrier signal with respect to a reference AC signal then determines the polarity (not the magnitude) of the demodulator output. The reference signal must be derived from the AC supply voltage of the transducer or from the chopper activation signal (see Figure 5.8).

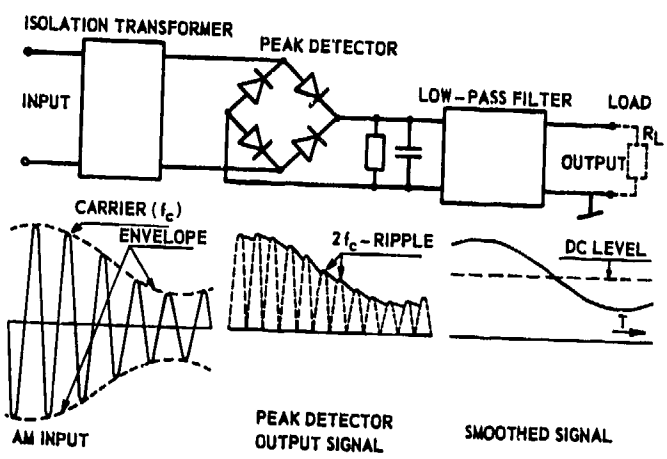


Figure 5.19 Single-phase full-wave bridge rectifier applied as an AM demodulator

Demodulation of a frequency modulated signal is called discrimination. Figure 5.20 shows a simple FM discriminator. The FM input is amplified, limited and differentiated, so that a series of very sharp pulses are produced. When a positive pulse enters the flip-flop circuit, this starts to produce a constant-voltage output; the same pulse also starts a time generator, which resets the flip-flop after a fixed time delay which is shorter than the shortest period of the FM signal. The output of the flip-flop is, therefore, a train of pulses of constant heigth and constant width, the frequency of which is equal to the frequency of the original FM signal. After filtering a DC signal is produced which varies linearly with the FM frequency.

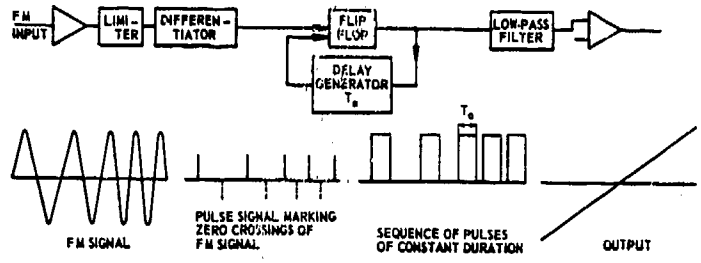


Figure 5.20 FM discriminator based on counting the number of zero crossings per second

The main disadvantage of the circuit of Figure 5.20 is that the flip-flop may also be activated by noise signals. Therefore, sometimes, more complex discriminators are used, which are generally based on the principle of synchronous detection. In these discriminators a secondary FM signal is generated which is sufficiently free from noise to be detected by a circuit like that described above; a servo circuit keeps this secondary signal synchronous with the original FM signal. This servo will only accept pulses which arrive near the time at which a new pulse could be expected to arrive on the basis of the secondary signal and will only allow the frequency of that signal to change relatively slowly. The discriminator will, therefore be much less sensitive to spurious pulses than the circuit of Figure 5.20.

A PDM signal is demodulated by passing it through a low-pass filter, as already described above.

Demodulation of PCM signals is called digital-to-analog conversion. There are many types of D/A converters. The most important of these are described in References 2 and 3.

5.3.4 Commutation

Commutation is a type of signal conversion which is different from the other types mentioned here. The type of signal (usually a DC signal or a digital signal) is not changed, but it is sampled at periodic intervals. This technique is extensively used in flight test instrumentation as it provides the possibility to record or telemeter several low-frequency signals on one channel. Though a large part of the original signal is discarded, the accuracy of the sampled signal need not be significantly lower than that of the original continuous signal if the sampling frequency is sufficiently high. The relation between sampling frequency, accuracy and the spectrum of the original signal is discussed in detail in Chapter 6.

A commutator is in principle a group of switches which successively connect a number of input signals to a common output line. The duration of each sample is short with respect to the period between successive samples of the same parameter. After decommutation the signal will have the shape shown in the upper part of Figure 5.21: a hold circuit will keep the value constant until the next sample comes in. If the signal changes during the period between samples, the error will increase with time between the samples. If correct values must be obtained between samples, interpolation will be necessary. Interpolation processes are described in Chapters 6 and 12.

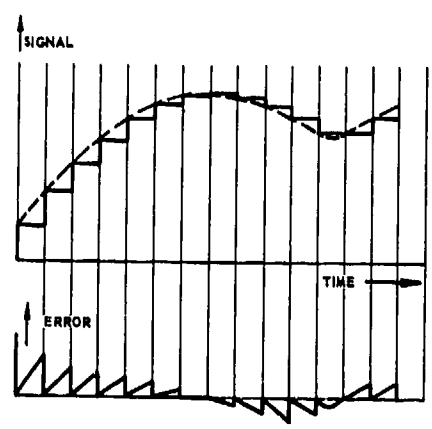


Figure 5.21 Reconstruction error of a sample and hold operation

Commutation can be applied to analog and to digital signals. Usually only the "hot" signal line of high-level analog or digital signals is switched, the signal return lines are all grounded at a common point (Figure 5.22a). The effect of interference and of ground currents in such a circuit would be unacceptable for low-level signals. In low-level multiplexing the two signal lines and the cable shields are scanned simultaneously, as shown in Figure 5.22b. Some types of analog signals, such as synchros, have more than one signal line; hence the number of switches per channel must be increased accordingly. If transducers for which the output signal is proportional to the power supply voltage are used, it may be necessary to scan the supply voltage simultaneously with the signal so that the ratio of the two can be determined. For parallel digital inputs, the number of switches must be equal to the number of bits.

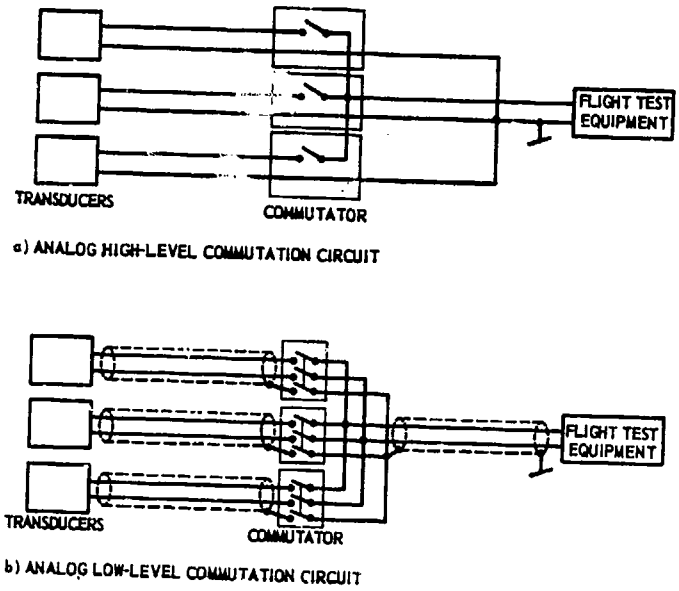


Figure 5.22 Commutators

Most modern flight test commutators use solid state switches. Matched diodes, field-effect transistors (FET) and metal-oxide semiconductor transistors (MOST) are extensively used for fast, reliable switching. The most important characteristics of commutators, especially when switching low level signals, are: the ratio between the impedance in on and off condition, offset voltages and currents in semiconductors, thermal e.m.f. in connections and the crosstalk between the different channels of the commutator. Relay switches are still used for high-accuracy, low level measurements. Normal relays cannot be used for commutation rates higher than a few samples per second, but reed relays are effectively used to up to 200 samples/sec. As solid-state switches are improving, they gradually replace the relays even in the more sensitive applications.

5.3.5 Analog-to-digital conversion

Digital signals are either parallel or serial. In parallel digital signals each bit is transmitted along a different signal line. They can be recorded simultaneously on different tracks of a tape recorder. A serial digital signal is transmitted along a single signal line, the different bits being transmitted consecutively. Serial digital signals must be used in telemetry, but are also used in some modern tape recording systems (see Chapter 9).

The majority of analog-to-digital converters require either a DC signal or a pulse signal as an input. Converters exist which can directly convert AC signals, synchro signals, etc. to digital numbers but often these are rather complex and relatively slow (they must receive at least one period of the 400 Hz signals, and usually more than one, before they can start the digitizing operation). Consequently, in most flight test instrumentation systems the transducer outputs are first converted to DC or to a pulse train before they are digitized.

Analog-to-digital conversion of Pulse Repetition Rate (PRR) signals is effected by electronic counting methods: either the number of events (pulses) per unit time ("EPUT") is measured, or the duration of the interval between successive

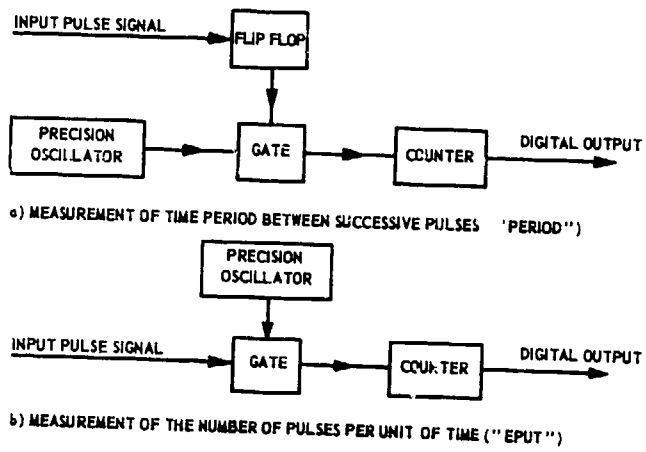


Figure 5.23 Analog-to-digital conversion of pulse signals

pulses ("PERIOD").

If the pulse frequency is relatively low, the time period between pulses is measured (Fig. 5.23a). The first incoming signal pulse sets a flip-flop, which opens the gate. This gate switches pulses from a precision oscillator to a counter. The second signal pulse resets the flip-flop, so that the gate closes. The number of oscillator pulses which have actuated the counter is then presented in digital format.

If the pulse frequency is relatively high, the EPUT method is used (Fig. 5.23b). A precision oscillator opens the gate during a fixed time period, and the counter determines the number of signal pulses which have passed the gate during that time period.

The resolution of the digital number is equal to the inverse of the number of pulses which have been counted. If a high accuracy is required, the frequency of the oscillator must be high in the case of the circuit of Figure 5.23a, and the measuring period must be long in the case of the circuit of Figure 5.23b. This latter measuring period will often be determined by the commutation rate of the flight test instrumentation system. If this causes the measuring period to be too short, it will be necessary to increase the number of signal pulses by applying frequency multiplication to the original pulse signal.

Analog-to-digital conversion of DC signals can be done in a number of ways. The most generally used methods are:

- Successive approximations (Fig. 5.24a). In this method the DC input voltage is compared to voltages derived from a reference voltage. The principle will be explained from the example given in Figure 5.24a. In the first step the input voltage is compared to half the reference voltage; as the input voltage is larger, the most significant bit is 1. Then the switching logic produces a new comparison voltage which is 3/4 of the reference voltage; as this voltage is larger than the input voltage, the second bit is zero. At the third step the comparison voltage is again decreased by half the previous step and produces 1 as a third bit because the input signal is larger than the comparison voltage. Successive approximations are made in this way until the required number of bits has been determined. The switching logic is controlled by a time base so that the successive bits appear at constant time intervals as a serial digital signal. If a parallel digital word is required, the successive bits are stored in a memory until the measurement is complete; the memory is then read out in parallel before the next measurement starts.

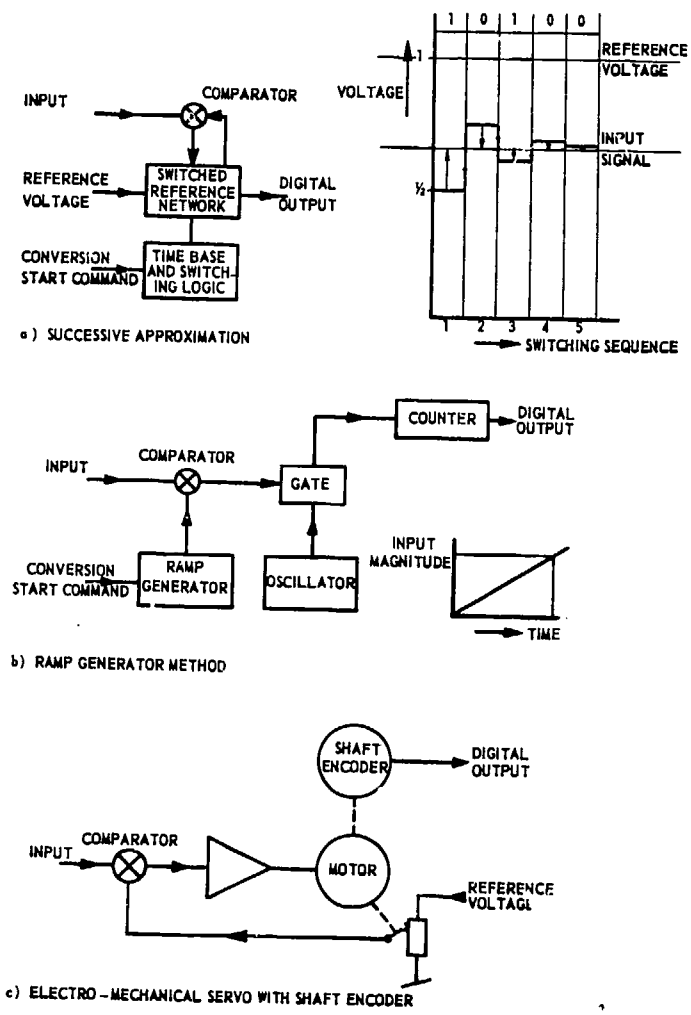


Figure 5.24 Methods for A/D conversion

- Ramp generator method. (Fig. 5.24b). In this method the measurement is reduced to a time measurement, as in the pulse signal digitizers described above. The signal voltage is compared to the output voltage of a so-called ramp generator, which produces a voltage which increases at a constant rate with time. As long as the signal voltage is larger than the output of the ramp generator, pulses from a precision oscillator pass through a gate to a digital counter. The gate is closed when

the ramp voltage equals the input signal voltage. The number of pulses counted is thus proportional to the input signal voltage.

- Electromechanical servo with digital shaft encoder (Fig. 5.24c). Here the signal voltage is compared with a voltage taken from the reference voltage by a potentiometer. If these voltages are not equal, the difference is amplified and drives a servo motor. The wiper of the potentiometer is driven by the motor axis and is, therefore, rotated until the voltage difference at the comparator is zero. A digital shaft encoder of the type shown in Figure 4.11 is also mounted on the motor axis. When the servo is in the equilibrium position, the digital output of the encoder is a measure of the input signal voltage.

The circuits shown in Figure 5.24 show only the basic configuration of some analog-to-digital conversion methods. The actual converters incorporate many additional features which improve the performance of the basic system. For instance, the first two methods mentioned above can produce large errors if the input signal should change rapidly during the aperture or if a large interference "spike" should occur during that period. These effects can be overcome by adding an "integrating circuit". Many other design finesses are required to obtain an accurate and reliable operation.

5.4 CONCLUSION

The design of signal conditioning circuits is a very complex task if the requirements of accuracy and reliability are high, as they usually are in flight test instrumentation systems. In this chapter only very general aspects of the design problems have been touched upon, in order to indicate the extent of the problems to engineers not specialized in the field of electronics and to give a general indication of the types of solutions which are in use. More detailed information on many of the aspects mentioned in this chapter and on the detailed design of the different signal conditioning circuits is given in the references below.

5.5 REFERENCES

1. Kandoian et al. — Reference data for radio engineers, Howard W. Sams and Co., Inc.
2. H. Schmid — Electronic Analog/Digital Conversion, Van Nostrand Reinhold Company, 1972.
3. W.P. Dotson, J.H. Wilson — A Digital-to-Analog Conversion Circuit using third order polynomial interpolation, NASA TR R-382, 1972, NTIS.

CHAPTER 6
SAMPLING AND FILTERING

by

L.W. Gardenhire

6.1 INTRODUCTION

Sampled data have been collected in flight testing almost from the beginning. Pilots or flight observers wrote down, more or less periodically, data from pointer instruments from the very early days onward and the first automated flight test data collection systems were photo-panel recorders which periodically provided pictures of an instrument panel. Such data collection methods were limited to very low frequency data, though the human observer could, under some circumstances, act as a very efficient filter in separating higher-frequency noise from the low-frequency data of interest.

With the advent of digital recording and telemetry systems and the tendency to use these for higher-frequency data, a thorough understanding of the characteristics of data sampling has become essential. The basic idea behind data sampling is, that a continuously recording data channel provides redundant information, i.e. the original information contained in the continuous recordings can be reconstructed with sufficient accuracy from a limited number of periodic data samples. This provides the opportunity to record samples from other data channels during the intervening periods, thus increasing equipment utilization and efficiency. If all data channels of a modern flight test instrumentation system had to be recorded or telemetered continuously, the data collection systems would become prohibitively large.

Even if the sampled data points exactly represent the values of the input signal at the moment when the samples were taken, the waveform reconstructed from these samples will never be exactly the same as the input waveform. In order to gain an understanding of the errors involved, it is convenient to divide them into two types:

- aliasing errors or "errors of commission", which are caused by the sampling process itself. In Section 6.2 it will be shown that these errors manifest themselves during the reconstruction of the waveform by the transformation of high-frequency components (with frequencies above half the sampling frequency) into components with frequencies below half the sampling frequency
- "errors of omission", which are changes in the amplitude and the phase of components of the signal caused by the characteristics of the interpolation process or the interpolation filter used for the reconstruction of the waveform from the samples. Similar errors can also be introduced by pre-sampling filters.

The magnitudes of both types of errors depend on the spectrum of the original signal, on the sampling rate, and on the method of interpolation used. It is, therefore, impossible to provide simple general rules for choosing the sampling rate and the characteristics of the interpolation process required to reconstruct a given input signal with a certain accuracy. In the first sections of this chapter the effects will therefore be analyzed by using a generalized type of input data spectrum and a representative number of interpolation processes. In Section 6.6 the effect of other types of the data spectra will be discussed.

The discussions in this chapter have been confined to periodic sampling methods. When extreme economy of power and bandwidth is required, as in missile testing, methods must be used in which redundant information is suppressed as much as possible before transmission or recording. These methods are indicated by the general name of source encoding (Ref. 6). A number of different approaches are possible, called data compression, redundancy reduction, asynchronous sampling, etc. These methods are not yet used in present-day flight testing but may become important in the future.

6.2 ALIASING ERRORS OR ERRORS OF COMMISSION

The basis for understanding these errors is the sampling theorem developed by H. Nyquist in 1928. This states that 2f independent samples per second are sufficient to completely characterize any signal containing only frequency components smaller than f Hz. Much has been written about this

theorem; however, most of the discussions assume ideal band-limited data and ideal filters, and do not take into account the practical limitations of filters or the information content of the data to be sampled. As a result, engineers have over the years, developed rules-of-thumb to cope with the sampling errors. The most widely accepted approximate sampling theorem is grossly misleading. It is generally quoted as: "Five samples per cycle of the highest frequency of interest is required to represent the function". This approximation has two shortcomings: First, the highest frequency of interest is not the determining factor, i.e. if frequencies higher than those of interest are present in the signal, they will also affect the measurements made at the frequencies of interest. Second, there is no indication of the magnitude of the error to be expected when using this criterion.

The errors which occur if the conditions of the sampling theorem are not met, are called errors of commission or aliasing errors. Figure 6.1 illustrates the general principle involved. On the left, a one Hz sine wave is sampled at 8 samples per second, and recovered to a fair accuracy in the lower left. The 7 Hz sine wave shown on the right side of the figure is sampled with the same sampling rate, which now is equivalent to 1 1/7 samples per cycle. The reconstructed function on the lower right gives an entirely different frequency (1 Hz), which is equal to the difference between the sampling rate (8 Hz) and the signal frequency (7 Hz). It will be clear that, if the input signal had a 1 Hz component which was "of interest" and a 7 Hz signal which was "not of interest" and if the signal was sampled at 8 samples per second, then the 7 Hz signal would appear in the reconstructed waveform as a spurious 1 Hz signal which distorts the original 1 Hz signal. It will also be clear that the samples themselves would be correct, but that the aliasing error is introduced during the reconstruction of the signal from the sampled data.The aliasing error is, therefore, a part of the interpolation error.

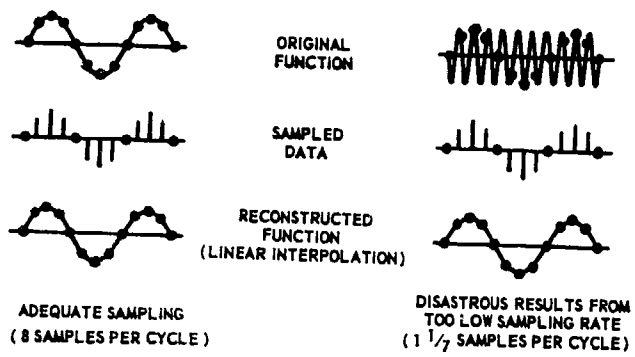


Figure 6.1 Illustration of the sampling theorem in time domain

A more general approach can be made when considering the amplitude spectrum of the data (Fig. 6.2). The Nyquist rate ("two samples per cycle") is based on ideal data with an infinite cut-off at a frequency f_i (Fig. 6.2a). This band-limited data has no frequencies above f_i. Figure 6.2b shows the amplitude spectrum of such data which has been sampled at a rate f_s slightly higher than 2 f_i. An image-like spectrum is formed around the sampling frequency. This is the sampling frequency plus and minus the information frequency. A series of these images appear around multiples of the sampling frequency. The amplitude of each image is a function of the sampling duration and, if this duration would be infinitely small, the amplitude of all images would remain the same to infinity. In actual practice, however, the only concern is the first few images. If the sampling frequency is slightly higher than 2 f_i, there will be no overlapping (foldover) frequencies produced that fall within the passband of the data.

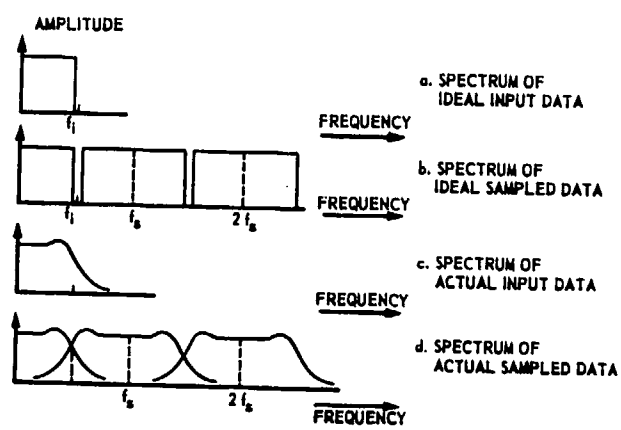


Figure 6.2 Ideal and actual sampled data in the frequency domain

Actual data usually looks more nearly like that in Figure 6.2c. If the data of interest is between the frequencies 0 and f_i, one can see that a considerable part of the spectrum exists above f_i. This spectrum will cause large aliasing errors if the sampling rate is only 2 f_i, as seen in Figure 6.2d. The signal components at frequencies larger than f_i will be folded back into the region of interest between 0 and f_i.

There are, in principle, two methods by which the aliasing error can be reduced:

- by using a higher sampling rate, at which the error due to overlap is less than the allowed error
- by using a pre-sampling filter to limit the bandwidth of the signal which is to be sampled; the cut-off characteristics of this filter must be chosen so that the frequencies above f_i are sufficiently reduced in amplitude before the sampling process is performed.

It has been noted that, in practice, many instrumentation engineers are so concerned about this foldover that they tend to use pre-sampling filters in all channels. However, in doing this they may create other errors which in many cases can be even larger than the aliasing errors they attempt to avoid. These errors are due to the input filter altering the data in both amplitude and phase. Thus, the filter omits data frequencies before they are sampled and creates errors of omission. In the next section some general information about these errors of omission as related to the use of pre-sampling filters will be given. In general the best way to prevent aliasing errors is to increase the sampling rate.

6.3 PRE-SAMPLING FILTERS

The choice of a pre-sampling filter always involves a trade-off between the errors of commission and the errors of omission. It is apparent that a filter will distort the incoming signal and introduce an error of omission. In cases where simple lumped-parameter filters are used (Butterworth, Gaussian or binomial filters, see Ref. 6), the error due to these non-optimum types of filters may very well be greater than the reduction in the error of commission. In other cases only a small gain is obtained at the cost of additional complexity (see Ref. 1). As a result it appears that in most cases it is better to reduce the aliasing error by increasing the sampling rate and not to use pre-sampling filters. This is however, not true for all data spectra which occur in flight testing, as will be discussed in Section 6.6.

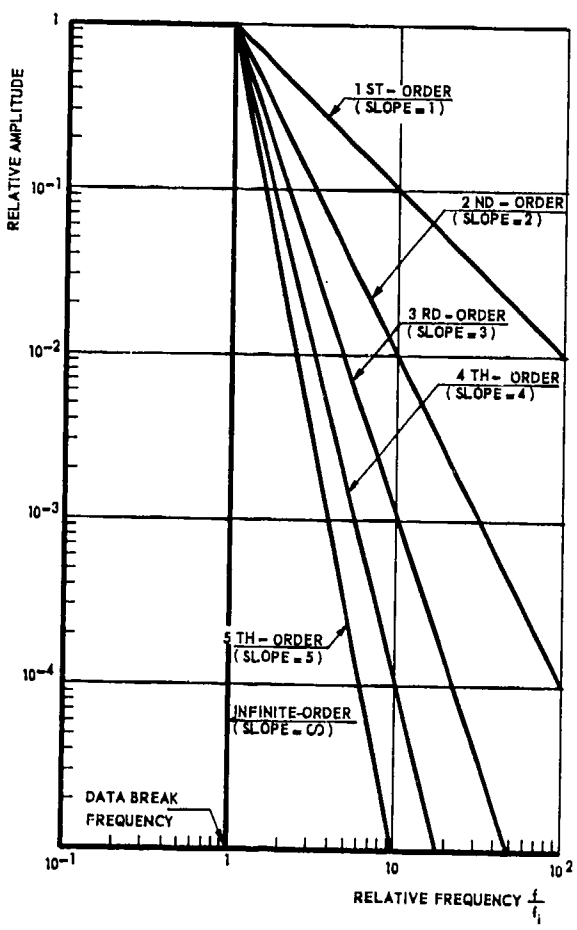


Figure 6.3 Generalized input data spectra for different orders of data

Analytical techniques exist for determining optimum pre-sampling filters based on the input data spectrum (Ref. 2 and 3). These filters are optimum in the sense that they minimize the mean square error of the output data waveform with respect to the input data waveform. The problem is that these filters can either not be realized or be so complex that nobody would attempt to actually build one. The knowledge gained from optimum filter performance provides, however, an insight in the performance limits of the system using non-optimum filters, and provides a measure of the efficiency of the non-optimized system.

It is of interest to give here an indication of the error of omission which can be expected when normal types of pre-sampling filters are used.

In order to simplify the treatment, a generalized shape of the input signal spectrum will be used. The input spectra are shown in Figure 6.3. The amplitude spectrum is flat up to a break frequency f_i, beyond which the data has a roll-off of various multiples of 6 dB/octave. These are described as "orders of data" (see also Chapter 3). First-order data (slope = 1, i.e. 20 dB/decade) rolls off at 6 dB/octave, second-order data (slope = 2) at 12 dB/octave, etc., with slope = ∞ for ideal band-limited data. These generalized spectra represent reasonably well the output of typical transducers to a white-noise stimulus. An accelerometer, for example, when submitted to a white-noise spectrum will produce a second-order data output. From studying actual data it has been found that most transducers have 1st-, 2nd- or 3rd-order characteristics. Higher-order outputs usually are the result of using a pre-sampling filter.

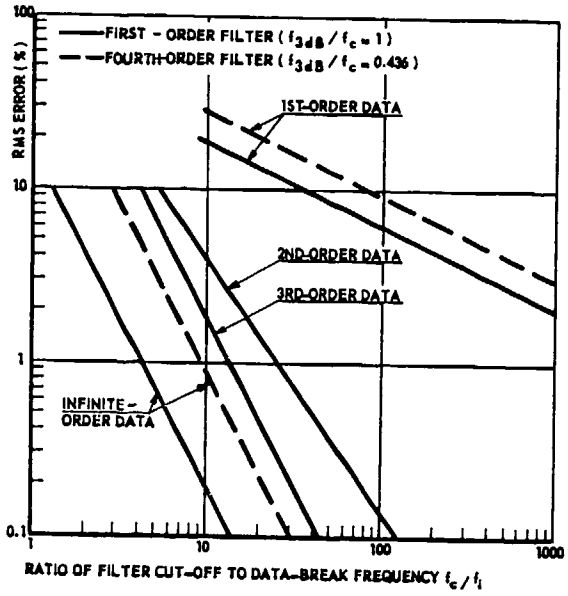


Figure 6.4 Errors of omission for first- and fourth-order binomial filters

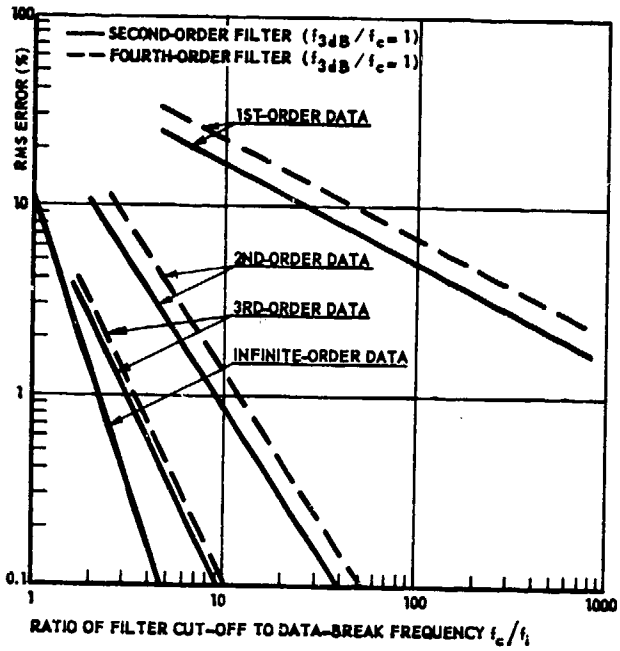


Figure 6.5 Errors of omission for second- and fourth-order Butterworth filters

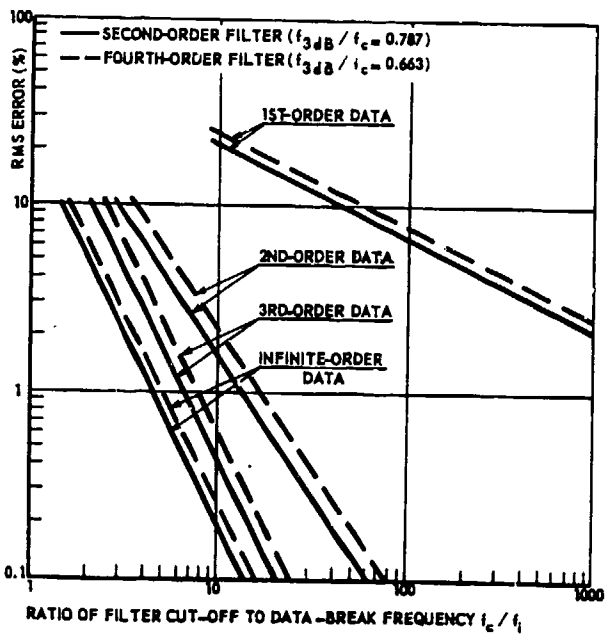


Figure 6.6 Errors of omission for second-and fourth-order linear phase (Gaussian) filters

Calculations have been made of the errors of omission caused to these spectra by three types of filters which are commonly used and easy to build. The filters are of the binomial, the Butterworth and the Gaussian types. The Butterworth and the Gaussian filters are described in Reference 4, for binomial filters see Reference 1. Calculations have been made for different orders of input data and for two orders of the filters. The choice of the type of filter depends on the data requirements: the Butterworth filters have the flattest amplitude response, the Gaussian filters have the most linear phase response while the binomial filter is critically damped.

Figures 6.4, 6.5 and 6.6 present the results of the calculations (see Ref. 5). The vertical scale is the rms difference between the input and output signals. The horizontal scale is the ratio of the filter cut-off frequency f_c to the data break frequency f_i. Both are defined as the frequency at which an extension of the constant

slope intersects with the unity amplitude-ratio value. The data break frequency f_i is defined in Figure 6.3. The filter cut-off frequency f_c is related to the 3 dB point on the amplitude characteristic of the filter. For a first-order binomial filter the 3 dB point and the cut-off frequency are the same: for a fourth-order binomial filter the ratio between these two is 0.44. For Butterworth filters the points are the same for all orders of filters. For a second-order linear phase filter the ratio of f_{3dB} to f_c is 0.79 and for a fourth-order filter it is 0.66.

It will be seen that for the rms values shown the curves are straight lines and the errors can become quite large, especially for low ratios of f_c to f_i. It will be clear that in many cases the rms error due to aliasing can be more easily reduced by choosing a higher sampling frequency than by adding a pre-sampling filter. Pre-sampling filters should in general only be used if the data spectrum is much different from those shown in Figure 6.3 or if the rms error is not the determining factor. Those cases will be discussed in Section 6.6.

6.4 INTERPOLATION

As mentioned before, the data samples provide the true values of the input waveform at the instant the samples were taken, assuming no other errors are introduced (e.g. by the use of pre-sampling filters). If values of the input parameter between samples must be known or if other processes, such as frequency analysis of the data, are required, interpolation is necessary to reconstruct the original waveform. The interpolation error is the difference between the input waveform and the reconstructed waveform, and is often expressed as a root mean square (rms) value. In some cases it may be desirable to express the interpolation error either as the amplitude error as a function of frequency, or as the maximum deviation between the input and output waveform. A number of these cases will be discussed in Section 6.6.

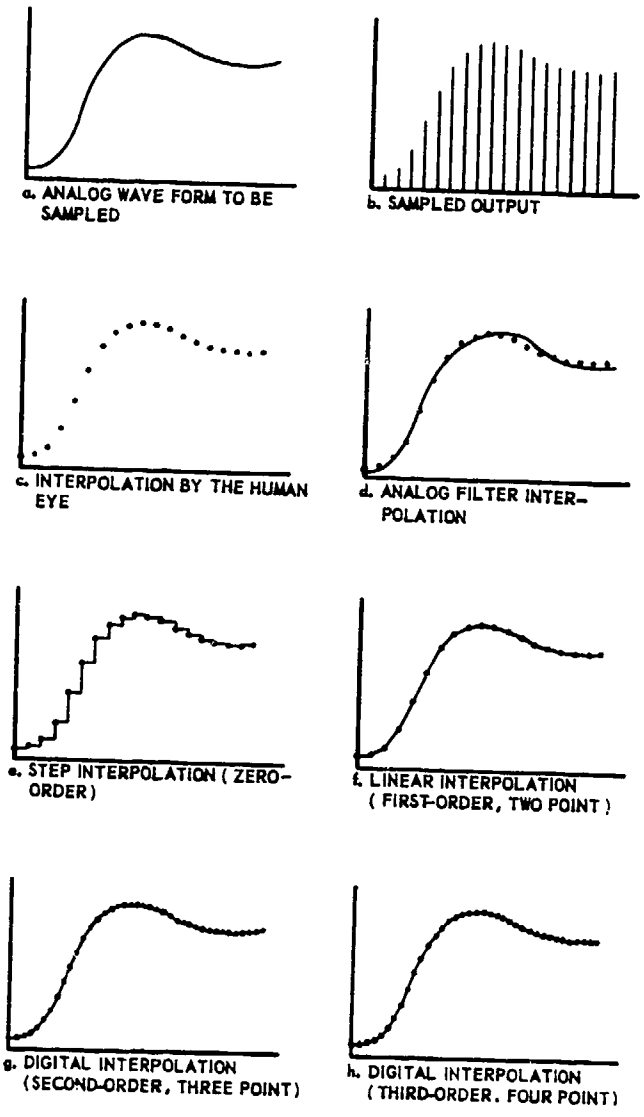


Figure 6.7 Interpolation processes

Interpolation will in general provide an approximation to the simplest curve through the values of the samples. This means that the spectrum of the interpolated curve will cut-off at one-half the sampling rate, and will include the lowest aliases of all components beyond that frequency. This was meant by the earlier remark that the aliasing error is part of the interpolation error. Even if no aliasing errors are present, the interpolation process will, itself, cause errors. These errors are comparable to the errors of omission of the pre-sampling filters, and will be designated by the same name.

There are many interpolation or reconstruction processes, both analog and digital. Some typical ones are illustrated in Figure 6.7 and will be briefly discussed here.

The simplest type of interpolation is visual curve fitting (Fig. 6.7c). The peak values of the sampled pulses (Fig. 6.7b) are viewed and mentally correlated to a smooth curve. The curve may be actually drawn by hand. This method is often used in quick-look analysis and in the processing of simple tests, but is not used when large quantities of data are processed.

A second method of interpolation is

analog filter interpolation (Fig. 6.7d). The sampled values are converted into voltages and sequentially fed into a low-pass filter whose output provides a continuous analog waveform which is a representation of the original waveform. The signal entering the filter may consist of sharp pulses as shown in Figure 6.7b or the voltage may be held in a pulse-stretching circuit until the next pulse arrives, as shown in Figure 6.7e. The latter process is mainly used since the pulse response of low-order filters is rather poor. If the pulse response of the filter is good, pulse-stretching is the equivalent of increasing the order of the filter by one. The analog filter method is only as good as the filter. The continuous curve produced by the filter will in general not go through the original samples.

When computers are used for data processing, the simplest process is step interpolation as shown in Figure 6.7e. In this process the step output of the pulse-stretching converter is used directly. Data values remain constant between samples and jump to the new value when the new sample is obtained. This is a zero-order process in that only horizontal lines are drawn and it can be represented by a zero-order equation. The advantage of this method over the analog filter method is that there is no error at the sampled values. The error builds up between the samples but returns to zero at the next sample.

A better approximation of the original waveform is obtained by linear interpolation (Fig. 6.7f). This first-order process consists of connecting adjacent samples with straight lines. If a value is needed between samples, the value is read from the straight line at the required time. Linear interpolation is a form of digital interpolation in that it uses a sample portion to determine values between the two samples.

Better approximations to the best fitting curve may be obtained by higher-order digital interpolation. Figure 6.7g shows the result of reconstructing the waveform by a second-order process, using three samples and inserting one secondary sample between each two samples. This secondary sample is calculated using the time correlation that exists in the three original samples. The method of calculating these secondary samples will not be covered in this chapter. It is, for instance, described in References 1 and 6. The waveform is reconstructed by connecting the secondary samples and the original samples by straight lines. Figure 6.7h shows the result of a third-order digital interpolation which uses the time correlation between four original samples; in this case three secondary samples are placed between each two original samples. The number of samples used and the secondary samples located can be increased to infinity. However, the complexity of the calculations increases greatly and even with an infinite number of secondary samples the interpolation error does not go to zero.

6.5 INTERPOLATION ERRORS

In order to show how to select the sampling rate based on the interpolation filter used, an example using actual data is presented. Figure 6.8 shows the spectrum of vibration data that has been filtered with a second-order pre-sampling filter cutting off at 600 Hz. The data were sampled at 6,000 samples per second or 10 samples per cycle of the break frequency. The first four sampling images, as they would appear mathematically, are shown. These images would all have the same shape, as shown in Figure 6.2, if they were linear plots. Logarithmic plots are shown in this case which is the conventional way of representing the frequency scale.

The images were produced by adding and subtracting the data frequency from the sampling frequency at a given attenuation level. For example, note that the data spectrum was at the 20-dB level at 2 kHz.

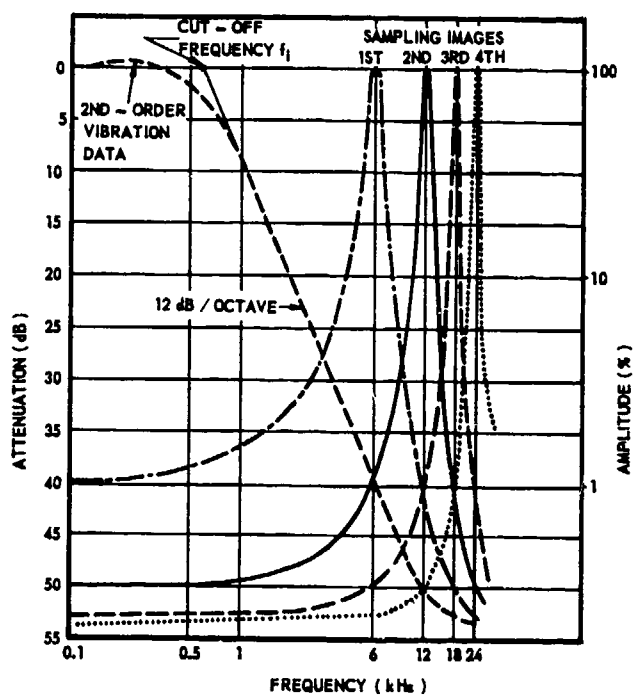


Figure 6.8 Images produced by sampling of second-order vibration data

Substracted from the 6-kHz sampling rate, this produces an image frequency of 4 kHz and, when added, produces 8 kHz. If this process is continued for all frequencies present in the data spectrum, the first image is produced. The higher images are formed in the same manner around multiples of the sampling frequency. These are seen in Figure 6.8 at 12, 18 and 24 kHz. There is an infinite number of these images, and if the sampling time is very small compared to the time between samples, their amplitude will remain the same.

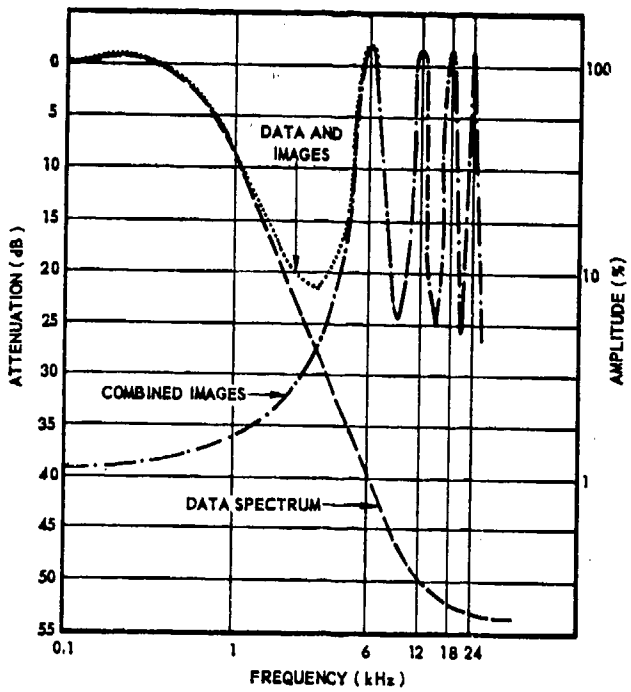


Figure 6.9 Results of combining the images and of combining the data and the images

In actual practice the individual images would not be seen separately but would appear as seen in the dot-dashed curve of Figure 6.9. The different image voltages are combined for a given frequency by taking the square root of the sum of the squares of all voltages present at that frequency. The combined image curve is thereby formed. Note that the fold-over error, produced by the combined image at the lowest frequencies shown, is just over 1 % or about 39 dB. This is the lowest error that can be obtained at this sampling rate, regardless of the interpolation process used, because this error occurs at zero frequency. If the sampling rate were increased to about 10 kHz (17 f_i), this error could be reduced to about 0.4 %. This is again the point at which the sampling frequency intersects the spectrum of the data.

The straight-line portion of the data spectrum (the slope which determines the order of data) does not continue to infinity but flattens out at some level due to noise limitations. This can be seen to be 53.5 dB at 30 kHz in this case. Increasing the sampling rate above this frequency will not improve the foldover error.

If one were to perform a spectrum analysis on this sampled vibration data, a spectrum as seen in the dotted curve in Figure 6.9 would be obtained. The curve is produced by adding the voltage of the data to that of the combined image at a given frequency.

Attenuation of these images is accomplished through the use of an interpolation filter cutting off at some frequency above the data break point and below the sampling rate. The filter break point and attenuation slope are important in obtaining an equal distribution between errors due to sampling and errors due to

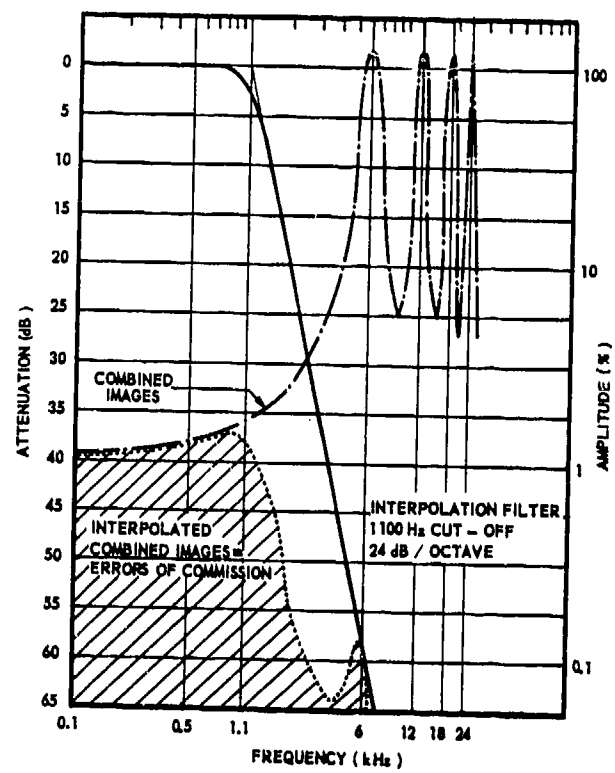


Figure 6.10 Suppression of the sampling images by the interpolation filter; errors of commission

the interpolation filter removing some of the data.

Figure 6.10 shows the effect of using a fourth-order (24 dB/octave) Butterworth filter, breaking at 1,100 Hz, on the sampling images of 600 Hz vibration data. No pulse-stretching has been used, the signal entering the filter is of the type shown in Figure 6.7b. The first image is attenuated to 58 dB or 0.14 % and the second image is below 65 dB. The total power under the dotted curve is found by integrating the power at all frequencies and comparing this with the total power under the data spectrum, yielding a total rms error of 1.6 %. This error is the error of commission referred to earlier, and is part of the total interpolation error.

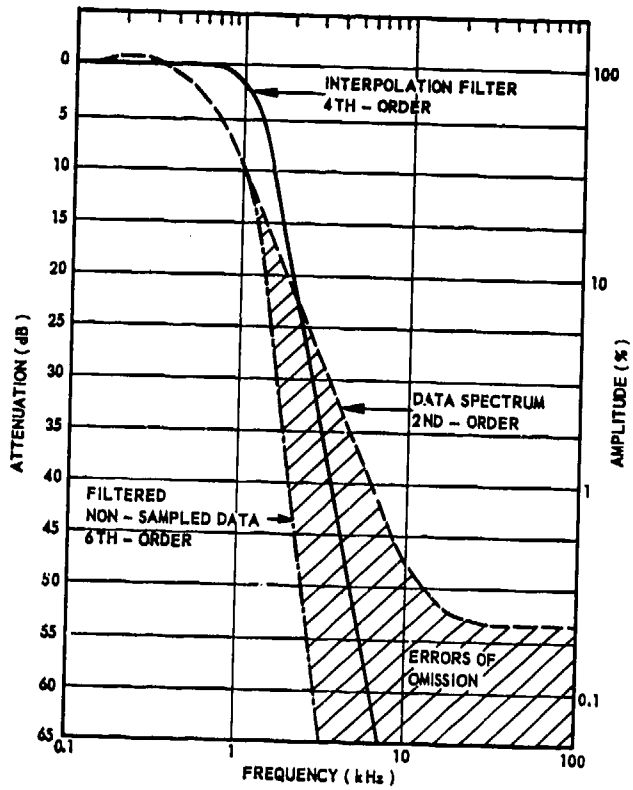


Figure 6.11 Errors of omission caused by the interpolation filter

In the process of suppressing the sampling images, this interpolation filter produced an error in that it removed part of the data spectrum. The result of this error is shown in Figure 6.11. The 1,100 Hz fourth-order interpolation filter removed 21.0 % of the original data spectrum, again based on the total rms power. This error of omission combined with the error of commission in Figure 6.10 makes up the total interpolation error, which would be the difference between the input and the output in the time domain.

Note that the filtered data rolls off at 36 dB per octave (sixth order), above the break point of the interpolation filter. This is because the slope of filtered data is the sum of the orders of the filter and the data.

Figure 6.12 shows the total result of the interpolation. The dashed curve shows the original data and the dot-dash curve is the interpolated data, including both errors of omission and errors of commission. The total rms error (21.1 %) is obtained by taking the square root of the sum of the squares of the two errors. This high error is caused by the low breakpoint of the interpolation filter and the resulting excessive error of omission compared to the error of commission. An optimum breakpoint would produce a more even balance between the two errors, resulting in a lower total error.

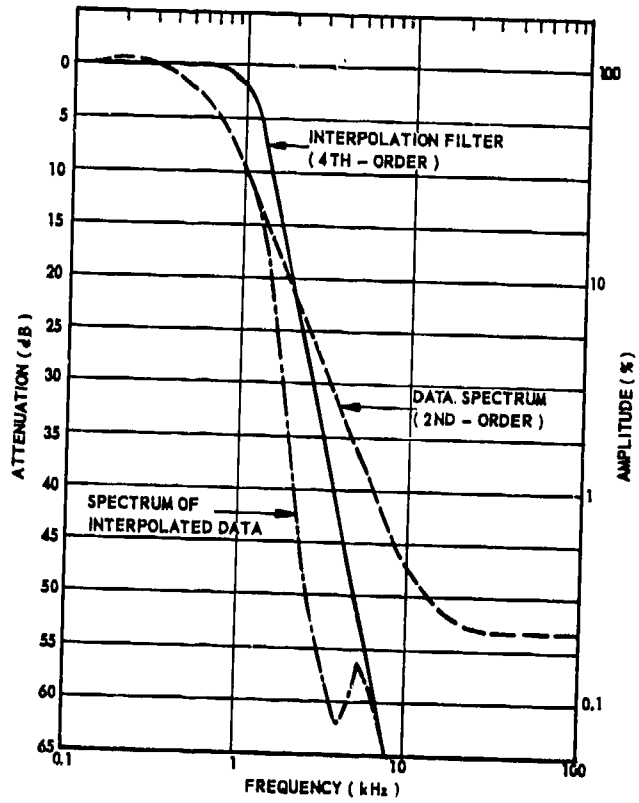


Figure 6.12 Total results of the interpolation of sampled data

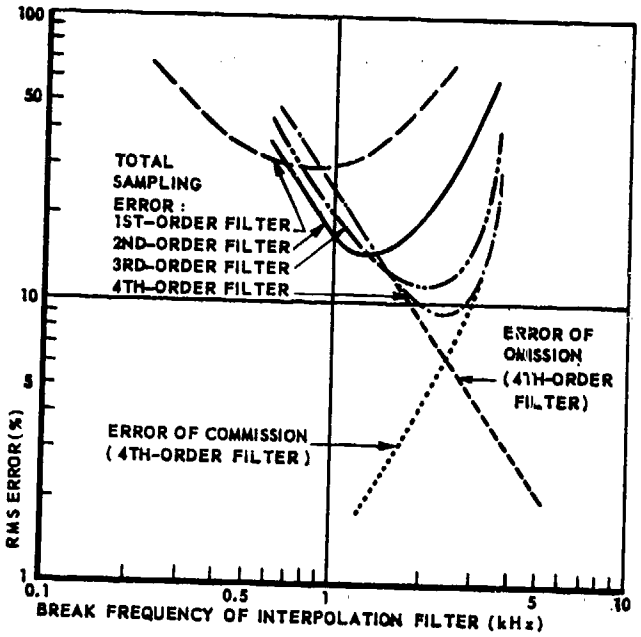


Figure 6.13 Sampling errors of the vibration data

Figure 6.13 shows how for the data of Figure 6.8 the errors vary with the break frequency of the filter. The dotted and the dashed lines show the errors of omission and commission for fourth-order filters of the type used in Figure 6.10. If the two curves are combined by taking the square root of the sum of the squares, the dot-dash curve results. The lowest point on this curve would be the optimum break frequency, 2,300 Hz in this case, decreasing the 21 % error to 9 %.

If the same procedure is repeated for first, second and third-order filters, the three upper curves are produced. The bottom of each curve represents the minimum rms error and, in turn, the optimum break frequency.

Note that the error is reduced greatly between first and second-order filters, about 15 % difference, while the difference between third and fourth-order filters is only about 3 %. As the order of the filter increases the interpolation error decreases, but due to the non-ideal data (2nd order) the error never goes to zero. In actual practice, the engineering optimum analog filter is one order greater than the order of the data; anything greater adds complexity to the filter with very little decrease in amplitude errors and phase error increase.

If the interpolation error is calculated for different sampling rates and orders of filters, using the optimum filter break frequencies, the family of curves shown in Figure 6.14 is produced. This is a plot of rms errors versus samples per cycle of f_i for the second-order vibration data, for different orders of interpolation filters. As the order of the interpolation filter is increased, the slope of the error curve approaches that of an ideal filter with infinite slope.

The slope of 3/2 is important, since it is an indication of the spectral content of data. For different orders of data this slope changes, first order is 1/2, third order is 5/2, fourth order is 7/2, etc.

All of the preceding results have been obtained with the impulse response of the interpolation filters. If a pulse-stretching technique (Fig. 6.7e) is used, better performance can be obtained, especially for lower orders of data and interpolation filters. As the order of the data gets higher, the pulse stretching is equivalent to an additional order of filtering; thus a second-order interpolation process results from the use of pulse-stretching and a first-order filter. The engineering optimum of the order of the filter now becomes equal to the order of the data.

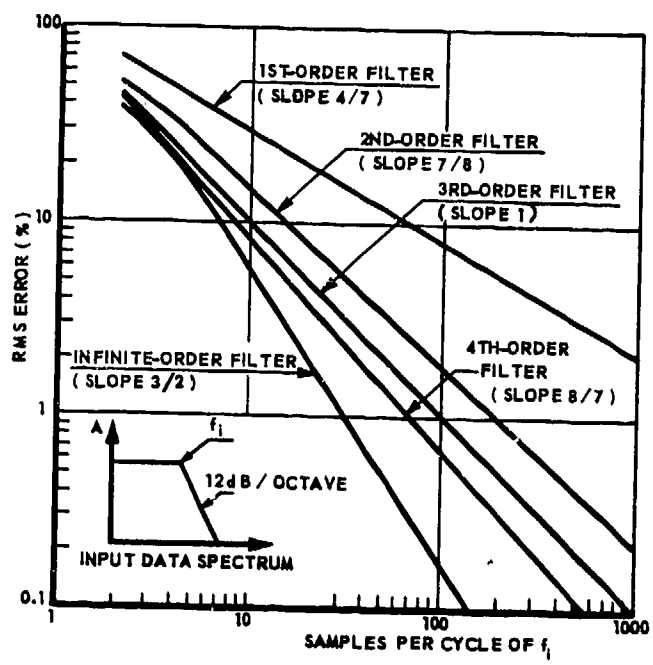


Figure 6.14 Interpolation errors for second-order vibration data (without pulse-stretching), using optimum break frequencies

If the process described above is done for four different orders of data, using pulse stretching, a family of curves as seen in Figures 6.15 through 6.22 are produced. There are two figures for each order of data. The first figure determines the proper sampling rate for a given rms error and filter, while the second figure shows the optimum break frequencies for different rms errors and orders of interpolation filters.

The set of curves are invaluable for selecting sampling rates and predicting interpolation errors when using analog reconstruction techniques. Note that in each case the slope of the interpolation-error curve approaches the Wiener optimum (infinite-order filter) as the order of the interpolation filter is increased. Also note that the Wiener optimum slope increases by the next higher odd number over two as the order of the data increases.

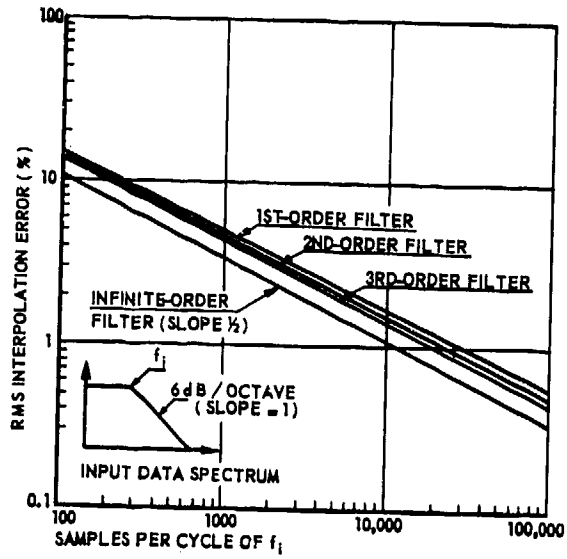


Figure 6.15 Interpolation errors for first-order data using Butterworth filters and pulse stretching

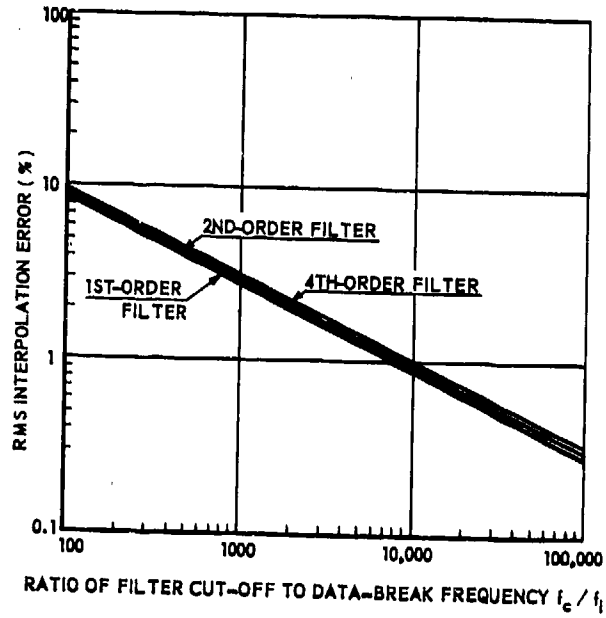


Figure 6.16 Optimum break frequencies for first-order data

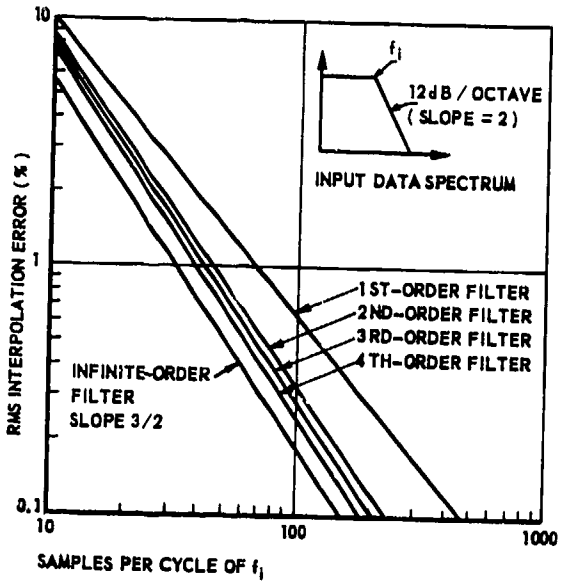


Figure 6.17 Interpolation errors for second-order data using Butterworth filters and pulse stretching

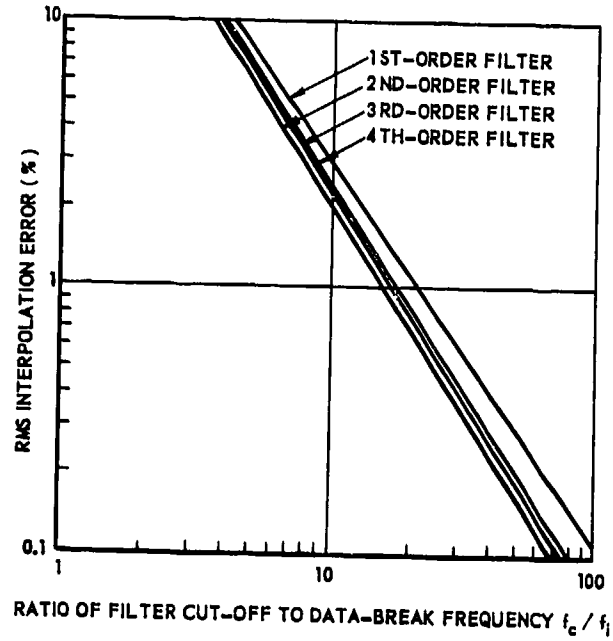


Figure 6.18 Optimum break frequencies for second-order data

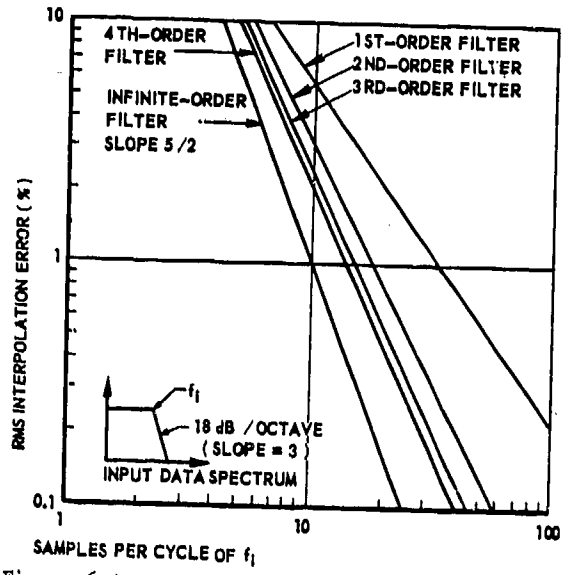


Figure 6.19 Interpolation errors for third-order data using Butterworth filters and pulse stretching

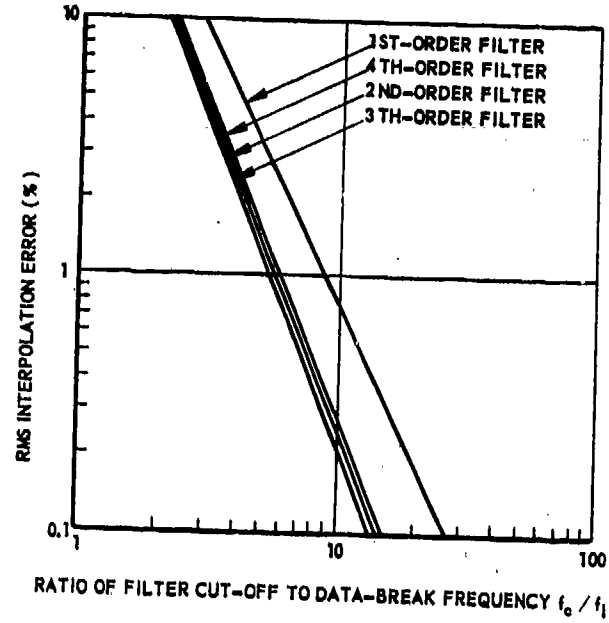


Figure 6.20 Optimum break frequencies for third-order data

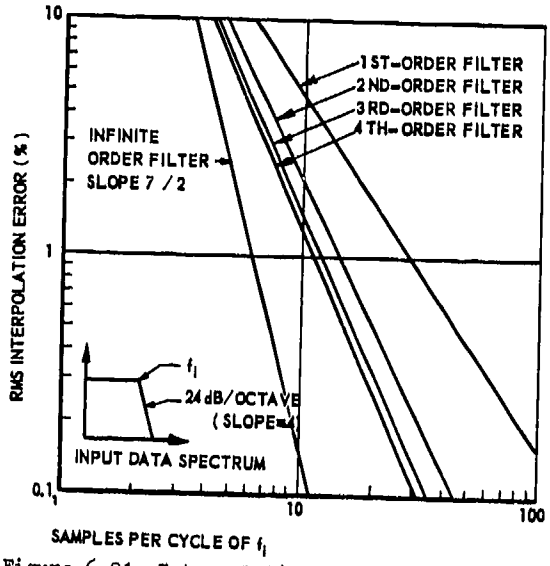


Figure 6.21 Interpolation errors for fourth-order data using Butterworth filters and pulse stretching

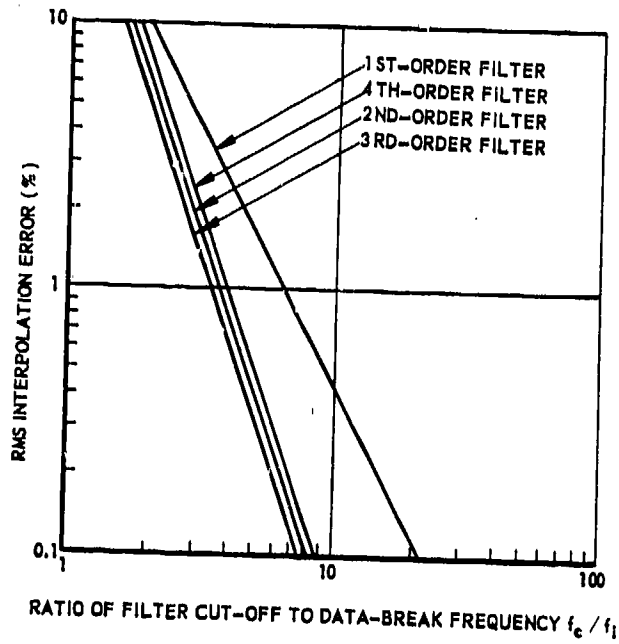


Figure 6.22 Optimum break frequencies for fourth-order data

Similar curves may be drawn for other types of analog interpolation filters (such as the Gaussian and binomial filters mentioned earlier) and for all kinds of digital filters. Examples of such curves are given in Reference 6. The curves given here will suffice for showing that the interpolation errors can become very large if proper care is not taken in choosing the break frequency and the order of the interpolation filter and the sampling frequency. They can also be used as an approximate indication of what will be attainable with other filter types of the same order. For more precise calculation the exact filter characteristic should be taken into account.

6.6 A FEW PRACTICAL OBSERVATIONS

There is one aspect which is very important in the spectra of flight test signals. That is, that very often there are parts of the spectrum that are of no interest to the measurement and may even obscure the information of interest in the signal. Examples of such unwanted signals are:

- the cables connecting a low-level transducer to the data collection system may pick up a strong signal from another data source or from the aircraft supply either by induction or capacitive coupling
- an accelerometer or rate gyro intended for the measurement of the motions of the aircraft may sense vibrations of the structure to which it is mounted
- a pressure transducer intended for measuring low-frequency variations in an airflow may also sense high-frequency pressure fluctuations due to small-scale turbulence.

These unwanted signals, which often have higher frequencies than the part of the spectrum which is of interest, can have relatively large amplitudes. They may make it necessary to use much higher sampling rates in order to keep the aliasing errors which they cause sufficiently small, or they may be suppressed by a pre-sampling filter. As mentioned in Chapters 4 and 5, a transducer with well-chosen frequency-response characteristics can often replace a pre-sampling filter in this respect. If the frequency of the unwanted signal is much higher than the highest frequency of interest, even a simple pre-sampling filter can effectively reduce its magnitude to an insignificant value without too much distortion of the signal of interest. If the difference in frequency is small, careful design of the pre-sampling filter will be required to keep the errors of omission sufficiently small. A spurious signal of a single discrete high frequency may be suppressed by a band-stop filter (notch-filter).

In some flight-test signals, the accuracy requirements for the low-frequency part and the high-frequency part of the spectrum are different. It may be that the low-frequency part should be measured very accurately, but that it will only be necessary to determine the presence or absence of high-frequency noise and, if present, its frequencies. In that case the rms criterion for determining the effect of pre-sampling filters is no longer valid. As most of the errors occur in the higher frequency region, they have less effect on the final result than would seem from their rms value.

When designing a sampled data channel, it is necessary to have a very good idea of the shape of the data spectrum which will occur during the measurement. It may be necessary to do some preliminary evaluation or even some preliminary tests in order to have sufficient information on which the choice of the sampling rate and the filter characteristics can be based.

6.7 CONCLUSIONS

The foregoing family of curves for the selection of pre-sampling filters, sampling rates, and interpolation filters are certainly not exact rules. The designer must consider his problem and apply the results accordingly. However, the importance and the difficulty of choosing appropriate values for the data spectrum and the allowable rms error should not be underestimated. It is unlikely that the user will always know ahead of time exactly what spectrum his data will have or what rms error he can allow. For this reason he must ask himself what data bandwidth the system must handle and what rms error it can introduce and still do the job which must be done.

Rms error is only one means of comparing input with output and in many cases is not the one to use. Sampling of picture data is a good example. If the picture is to be reconstructed for the eye to see, a much lower sampling rate can be used. The eye for instance is not capable of seeing large amplitude errors in a busy picture, yet it can see a small amplitude error in an unchanging area.

Sampling and reconstruction of flight test data has become the major method used in to-day's flight testing. Although there are many reasons for this, the most important are the ease of handling and the ability to maintain accuracy. The importance of understanding the data and, in turn, selecting the correct sampling rate and the proper interpolation process cannot be overstressed.

6.8 REFERENCES

1. D.D. McRae, E.F. Smith — Computer Interpolation, Advanced Telemetry Study, Technical Report No. 2, Part 1 and 2, Radiation Incorporated, 15 December 1961
2. J.J. Spilker — Optimation and Evaluation of Sampled Data Filters, Lockheed Aircraft Corp., Report LMSD-48335, 18 November 1958

3. A.J. Mallinckrodt, R.W. Stewart — Aliasing Errors in Sampled Data Systems, 24 August 1958, Ralph M. Parsons Co. Report

4. Reference Data for Radio Engineers, Fourth Edition, 1967, International Telephone and Telegraph Corp., Chapter 7, pp. 191-229

5. D.D. McRae — Interpolation Errors, Advanced Telemetry Study, Technical Report No. 1, Part 2, Radiation Incorporated, 16 March 1961

6. L.R. Gardenhire, T. Eisenman — Data sampling and filtering, AGARD Flight Test Instrumentation Series, Volume 8

CHAPTER 7
CALIBRATION

by

D. A. Tougas

7.1 INTRODUCTION

Measurement can be defined as the process of comparing the magnitude or intensity of a physical quantity to a reference value or standard in order to determine a numerical value of that physical quantity. In the early times standards were usually defined in such a way that everyone who wanted to make a measurement had direct access to the standards. For instance, standards of length were the width of a thumb, the length of a foot, the distance covered in one stride, etc. As greater accuracy became necessary and more physical quantities had to be measured, international standards were adopted. Standards in different countries were either compared periodically to each other or the methods for deriving them were so exactly prescribed that they could be reproduced with sufficient accuracy. This development led to the establishment, in 1875, of the International Bureau of Weights and Measures at Sèvres, France. The standards preserved there are the international reference standards or primary standards to which all other standards can be compared.

From these primary standards a complex echelon of subordinate standards is derived. Each technically developed country has its Standards Bureau or Laboratory, which has secondary standards that are directly derived from the primary standards. Many major industries and research laboratories have tertiary standards which are derived from the secondary standards. The lower standards are all periodically compared to a standard one order higher to determine their validity as a standard. The measuring instrument is at the lowest level of this network.

Calibration is the process of determining the measuring characteristics of an individual instrument or measuring chain, with the accuracy required for a particular application, using suitable standards as a reference. In general, previous knowledge of the general characteristics of the instrument type will have been available when the instrument was selected for the application. The calibration will then establish precisely the relation between input and output of the particular instrument and will be the basis for a check of its accuracy.

The final object of a calibration is to determine the characteristics of a complete measuring chain. In practice it is often preferable to calibrate each component of the measuring chain separately (see Section 7.7). These component calibrations are then combined to determine the overall (end-to-end) calibration of the measuring channel. If an overall calibration of the measuring channel is made in one step, it can be regarded as a component calibration of a channel with only one component. Therefore, most of what is said in this chapter about component calibrations is equally applicable to cases where the overall calibration of the channel is made directly.

The calibration engineer uses the information provided by the calibrations to establish:

- that each component functions properly
- the relation between the physical input and the output of the complete measuring chain, which is used to convert the measured data to engineering units during processing
- the accuracy with which the measuring system follows this relation.

7.2 THE SCOPE OF CALIBRATION

7.2.1 Complete calibrations

In any practical application the output of a measuring channel will not only be determined by the magnitude of the parameter which it should nominally measure, but also by the magnitudes of physical quantities other than the one that must be measured. A measurement of a pressure difference, for instance, may be influenced by the pressure level at which the measurement is made, the temperatures of the different elements of the measuring chain, the acceleration to which the transducer is subjected, the supply voltage, etc. If an accurate measurement is to be made, these influencing quantities should also be measured simultaneously with the measurement of the input parameter. A

calibration then must also include a determination of the sensitivity of the output of the measuring system to each of these environmental parameters.

A complete calibration, i.e., a complete determination of the measuring characteristics of a particular instrument for a particular application, should therefore not only concern the parameter which is nominally measured by the measuring channel, but also the other parameters which can affect the output. As the calibration relating to the nominal input parameter is usually broken down into a static and a dynamic calibration, a complete calibration usually consists of three parts:

- A static calibration related to the nominal input parameter. This gives the relation between the input value of this parameter and the output of the instrument or component, provided the input parameter is varied so slowly that the dynamic characteristics of the measuring system do not affect the output.

  A dynamic calibration which usually gives, as a function of frequency, the amplitude ratio (i.e. the ratio between the measured output amplitude and the value which this amplitude should have according to the static calibration) and the phase angle between input and output.
- Environmental calibrations. These should include all environmental parameters which can affect the output. As the sensitivity of the output to these environmental parameters usually is much less than the sensitivity to the nominal input parameter, the accuracy required for these calibrations often is not very high.

In each calibration, whether static, dynamic or environmental, a standard should be used to measure the input parameter and another standard to measure the value of the output. The accuracy required of these standards must be derived from the accuracy specified for the measurement. This accuracy is usually specified as a total error which must not be exceeded with a certain probability (see Section 3.3 of Chapter 3). Since the calibration error is one of the errors included in the total error it must be sufficiently small, so that the total error does not exceed the specified value. High-accuracy calibration standards are costly and the time required to execute a calibration usually increases with the accuracy. It is, therefore, advisable to use a standard which provides just the required accuracy (see Section 7.3).

7.2.2 Limited calibrations

A complete calibration as described in Section 7.2.1 will in general be a complex and time consuming exercise. In practice the procedure is usually simplified considerably, but this can only be done under specific circumstances. These are:

- that the ranges and frequency spectra of the nominal input parameter and of the environmental parameters for the particular application are specified to a sufficient degree
- that previous knowledge of the measuring characteristics of the instrument is available, either from previous use and calibration of the instrument or from manufacturer's specifications
- that the accuracy of the particular measurement for which the calibration must be made is well specified.

If these requirements are met, the calibration engineer may decide that certain parts of the complete calibration procedure need not be executed for a particular test. Such a decision can only be made if the calibration engineer is satisfied that his previous knowledge is applicable to the specific circumstances of the test within the specified accuracy requirements. He may decide, for example, that a certain environmental parameter, within its specified range, will have a negligible effect on the accuracy. It is also possible that he is satisfied that the effect of a certain parameter can be corrected on the basis of results of previous calibrations or of manufacturer's data. In that case, the value of the parameter concerned must be measured during the test also.

When making this judgement it must be kept in mind that the "previous knowledge" may not be applicable to the circumstances of the test for which the calibration is made. Some possible reasons for this are:

- the environmental conditions during previous calibrations differed from those of the test (the manufacturer's test conditions are frequently not fully specified)

- the characteristics of the instrument may have changed since its last calibration because of ageing or damage.

The static calibration will only be deleted on rare occasions. Even when a very low measuring accuracy is required, it will generally be better to run a static calibration because this will at least provide assurance that the instrument functions properly (see Section 7.4). The dynamic calibration and many or all environmental calibrations can often be deleted or can be made at considerably longer intervals than the static calibrations. After a major repair of the instrument a more complete calibration will often be required.

7.3 STANDARDS

Primary standards have been defined for the seven basic units of the International Standards System. These are:

- length (meter)
- mass (kilogram)
- time (second)
- electric current (ampere)
- temperature (kelvin)
- light intensity (candela)
- atomic weight (mol)

Six of these units have been defined in such a way that a primary standard can be set up anywhere in the world; for instance the meter has been defined as a certain number of wave lengths of a well defined line in the spectrum of krypton 86 and a second has been defined as a certain number of periods of the wave emitted by a line in the spectrum of cesium 133. But the kilogram, which has been defined as the mass of a certain volume of platina-iridium preserved at the International Bureau of Weights and Measures at Sèvres, can only be calibrated by direct comparison with a higher standard at all levels. Standards for quantities other than the basic units of the IS system, such as those for pressure, acceleration, voltage, force, power, etc., must be derived from these seven basic standards.

As already mentioned in Section 7.1, our metrology system consists of several levels of standards, each being compared to the next higher order standard. The calibration of an instrument used for flight testing is done against a standard which is several levels removed from the international primary standard. The ability to verify this series of standards to the primary standard is called traceability. It is this traceability that gives credibility to the measurement and also this traceability, to an ultimate single reference, allows the test engineer to compare empirical data from different sources.

Standards are instruments which have been especially selected for stability and accuracy. The higher-order standards are used only for the purpose of calibrating standards one order lower. Only the lowest-order working standard is more or less continuously used for calibrating measuring instruments. It is so designed and constructed that the calibration specialist can have confidence in its accuracy. It should be compared to a higher-order standard at specified intervals.

The standards to be used in a particular laboratory should be procured to meet the specific accuracy requirements which will be needed. Accuracy costs money and as a general rule it can be assumed that, to obtain a standard of double the accuracy, the cost will increase four to ten times. Procurement of a standard significantly better than is required may well be economically wasteful.

The accuracy to which a particular instrument must be calibrated for a given measurement must be determined by an analysis of errors as described in Chapter 3. The ratio between the accuracy of the measurement and the required accuracy of the calibration standard will depend on the specific circumstances of the measurement. As a general guideline it is often said that the calibration standard should be five times more accurate than the measurement accuracy which is required. But in cases where there are other important error sources, i.e. where the total measurement accuracy requirements will tolerate a greater calibration error, the ratio can be much lower, down to 2 or less. The justification of the need for a more accurate standard should be very carefully considered.

7.4 STATIC CALIBRATION

Static calibration of the instrument against its nominal input is performed far more often than

any other type of calibration. When an instrument is selected for a particular measurement, it is usually chosen in such a way that the dynamic characteristics will not have a large influence on the measuring results. Then accuracy is primarily affected by changes in the static calibration and correction for dynamic effects can be based on much less frequently executed dynamic calibrations. The same also holds for environmental parameters: if the measuring system has been chosen so that their effect on the accuracy is small, corrections can be based on the information provided by previous calibrations.

The choice of the calibration standard has already been discussed in some detail in Section 7.3. When using an available calibration system for a new instrument, great care must be taken to ensure that no errors are introduced into the calibration by an interaction between the instrument being calibrated and the standards which are being used as a reference. The interaction which may occur is often quite subtle and difficult to recognize, but the errors which can be introduced may be of significant magnitude. This is one aspect of the concept of "finesse" mentioned in Chapter 3. Examples are excessive loading of an electrical standard, or temperature effects due to self-heating by electrical currents.

In general, the static calibration is performed by applying fixed incremental values of the measured parameter to the instrument and measuring the output signals. The inputs must be generated or measured by a properly calibrated and traceable standard of sufficient accuracy. The output is measured accurately using a method which is compatible with any further processing of the calibration data. For measuring systems with visual indicators this is usually done by carefully reading the indication and recording it on a specially prepared sheet. For measuring systems with an electrical output a properly calibrated indicator must be chosen so that it provides the same load to the output circuit as is used in the aircraft. If the calibration data are directly processed by a digital computer, the output can be measured by an instrument which directly provides a digital output in a format suitable for the computer.

As already mentioned in Section 7.1, each calibration should start with a <u>check on the proper functioning</u> of the measuring system. The first check usually verifies that there is an output of approximately the correct magnitude. A very efficient check for most instruments is to let the input vary slowly but continuously through the measuring range. A careful observer can detect irregularities in the rate of change of the output which may indicate mechanical damage or bad electrical connections. Experience will teach what other checks can be made to obtain information on the proper functioning of the different types of instruments. For instance, for pressure instruments the input is kept constant for some time at a suitable value as a check for leaks, and a step input may be applied to check whether the dynamic response is affected by obstructions in the tubing. When the calibration engineer is satisfied that the instrument functions correctly, the static calibration can be initiated.

The <u>number of points</u> used in the calibration must be sufficient to establish the complete calibration curve with the required accuracy. Here it is important that the final accuracy of the calibration be kept in mind. In cases where a high degree of accuracy is required it may be necessary to use a relatively large number of points. This is especially true when the input-output relationship is suspected or known to be non-linear. On the other hand, if the instrument being calibrated is considered to be much more accurate than the total requirements, very few points may be sufficient to provide the needed confidence. This can in some cases mean that the calibration equipment can be simplified: for example, for some accelerometers it may be sufficient to measure points at + 1 g, 0 g and - 1 g, which can be done using a sufficiently horizontal table and a simple bracket. In this case, the much more expensive equipment necessary for measuring other points will not be required. Similar methods can also be used if the calibration curve is not absolutely linear. For resistance thermometers and thermocouples a standard calibration curve for the particular material can be described by a 2nd or 3rd-order polynomial. This calibration curve is often given by the manufacturer; if that is not the case, it must be determined during a first calibration of the element. The later calibrations are then used to verify that the specific element under test does indeed correspond to the relevant standard calibration curve. In these cases, it will be possible to calibrate such a thermometer at only 2 or 3 points rather than covering the full range. When calibration methods like this are used,

the calibration engineer must be very sure that the polynomial is valid over the full range.

In some measuring systems environmental parameters, like the supply voltage or the FM carrier frequency, can produce shifts in the zero point of the calibration or in its average sensitivity without significantly affecting the shape of the calibration curve. In such cases one or two fixed voltage inputs are often recorded or telemetered once in every measurement cycle in order to provide a basis for correction. Such measurements are often called "calibration points" or "autocal". It must be stressed that this technique does not obviate the requirement for a normal calibration of each measuring channel and does not reduce the number of points required in the calibration.

An important aspect of static calibration methods is to eliminate dynamic effects. In the first place each measuring point must be allowed a sufficient settling time for the calibration standard and the measuring system to reach their steady-state values. Some instruments are also sensitive to the rate of change of the input parameter between successive calibration points. For some types of pressure instruments, for example altimeters and air speed indicators, the time during which a value must be kept constant and the rate of change of pressure between successive points is specified as part of the calibration procedure.

Another important point in calibration is hysteresis. If hysteresis occurs, it is necessary to calibrate the instrument first with increasing values of the measuring parameter and then with decreasing values, and to take at each point the average of the two. It must be kept in mind, however, that the magnitude of the hysteresis may depend on the range used. If during the flight test the input parameter will vary only over part of the total range of the instrument, it will be better to calibrate only over that range. If the hysteresis error is large with respect to the allowable total error, it is sometimes necessary to simulate the expected time history of the measurement during the calibration. Some types of hysteresis, such as that caused by backlash in gears, will not depend on the complete previous time history of the measurement, but only on the direction in which the input parameter changed at the particular moment of measurement. It is, therefore, important for the calibration engineer to understand the nature of the hysteresis before setting up his calibration program. The hysteresis may also depend on the vibration level to which the instrument is subjected. During calibrations where hysteresis is important, the instrument should therefore be subjected to the same type of vibration as is expected during the flight test.

Good calibrations can only be made if the calibration engineer understands the problems of his instrument and has built up sufficient experience with each instrument type and even with each individual instrument. It is, therefore, very important that all calibration results are stored in such a way that reference is easy. The calibration engineer should compare each calibration with the previous ones, in order to detect any changes that may have occurred. Every change in a calibration should be explained before the instrument is released for use. Such a comparison can be made during the calibration if the new values are recorded on a specially prepared sheet which also has the data from a few previous calibrations. If some processing has to be done before the final calibration results are available, and especially if the final calibration results are produced in a computer, the calibration department should approve the final results before the instrument is released. The calibration curve can be incorrect due to blunder errors, errors in smoothing, errors in combining different calibrations, etc., so that a positive final check by the calibration department is absolutely essential.

A digital computer is a very useful tool to aid the calibration engineer in performing his task. The derivation of an analytical expression to describe a best fit curve of even a moderate number of calibration points by manual calculations can be a formidable job, especially if a polynomial expression is required to achieve satisfactory results. On the other hand, the fitting of a relatively large number of calibration points with even a seventh or ninth-order polynomial is relatively simple when using a computer. In addition to performing the necessary computations, a computer system can provide plots or graphs and/or tabulated data, formatted for easy evaluation and containing other information to simplify the analysis of calibration results. When a number of components, individually calibrated, make up a single measurement channel, the combining of the individual calibration equations to a single expression required for flight data processing again can best be done by the digital computer.

7.5 DYNAMIC CALIBRATION

The object of a dynamic calibration is to determine the dynamic characteristics of an instrument or a measurement system. These dynamic characteristics are discussed in some detail in Chapter 3. They are usually given as the amplitude ratio and the phase angle as a function of frequency. Examples of such relations for second-order linear systems are given in Figures 3.6 to 3.8 of Chapter 3.

In many cases the instruments for a particular measurement have been chosen so that the dynamic effects can be neglected for the range of frequencies which will occur during the flight test. Then the dynamic calibration is only used to verify that this is true. But there are also many measurements in which sufficient accuracy can only be obtained if a correction is made for the dynamic characteristics. If that is the case, it is very desirable that the measuring system is dynamically linear, i.e. that its response can be described by a linear differential equation. For dynamically non-linear systems the correction becomes a very complex and arduous task. Fortunately, most instrument systems designed for dynamic use follow a linear differential equation sufficiently closely. This must, however, be verified during the calibration. The easiest method to do this usually is to apply the method of sinusoidal excitation described below with several amplitude values at each frequency. If the amplitude ratio is independent of the amplitude, it can be assumed that the system is dynamically linear.

As already mentioned in Chapter 3, it is essential that during the application of a dynamic calibration not only the amplitude ratio but also the phase angle is taken into account. In systems with a constant group delay the phase angle will cause a constant time delay between input and output; if the group delay is not constant over the range of frequencies contained in the signal, phase distortion will occur. An extreme example of this is shown in Figure 3.9 of Chapter 3. It is, therefore, essential that during a dynamic calibration both the amplitude ratio and the phase angle are measured.

There are two principal methods for determining the dynamic response of a measuring system:

- Sinusoidal excitation. In this method the instrument is subjected to a sinusoidally varying input, the frequency of which can be varied over the complete dynamic range of interest (Reference 1 and 2). The amplitude ratio between input and output and the phase angle between these two are then measured directly at a number of frequencies. From these measurements plots of the amplitude ratio and the phase angle versus frequency can be made.
- Pulse excitation. In this method the instrument is subjected to either a step function change in input or to a sharp input pulse (Reference 3, 4 and 5). In these techniques particular care must be exercised to avoid saturating or overdriving the instrument at any frequency. Utilizing Fourier analysis techniques on the output, the amplitude ratio and the phase angle at each frequency can then be calculated (Reference 6 and 7).

The excitation of signal conditioning networks or other components of a purely electrical nature is usually not too difficult because generators of electrical sine waves and pulses are readily available. Devices for accurate dynamic excitation of other physical parameters are much more difficult to obtain. Methods of dynamic stimulation of linear and angular displacements and accelerations, and of forces and moments, have been available for some time, but generators for high amplitudes and low frequencies (below about 15 Hz) are still difficult to obtain. In recent years a variety of methods of dynamic pressure generation have been developed, but even today the U.S. Bureau of Standards will only provide very limited dynamic calibrations of pressure beyond the normal range used for microphones (approximately 2 N/m^2).

It is, therefore, of the utmost importance that the requirements for dynamic calibrations are realistic. In most applications where the dynamic characteristics are significant, the accuracy requirements become lower as the frequency increases. The reasons for this can be different according to the application. A few examples are given below:

- Often a dynamic calibration is required to show that the amplitude ratio and the phase angle do not change significantly over a limited frequency range, and that certain higher frequency noise will be sufficiently damped. Then the accuracy required for these "noise frequencies" is much lower than is required for the signal frequencies of interest. The calibration must show that the high frequency noise will be sufficiently damped and that the effect of the dynamic response on the

low-frequency data, that must be measured, is negligible.

- In other cases it may be necessary to determine from the measurements whether there were high-frequency inputs and at what frequencies these occurred, but the accuracy requirements for the amplitudes of these high-frequency components are often much less than for the low-frequency signal. One must just know that they were there, but their exact amplitude is not of prime importance.
- Even when the high-frequency components of the signal must be accurately measured, the accuracy requirement often decreases with frequency. This is because in many measurements the signal amplitudes decrease with frequency. For a certain overall accuracy of the total measurement the accuracy requirement for the higher-frequency components will then be less than for the lower-frequency components.

7.6 CALIBRATION OF ENVIRONMENTAL PARAMETERS

A complete and comprehensive calibration of a test instrument or measurement system must take into account the environment in which it is to be used and the effect that these extraneous influences have on the accuracy of the measurement. Some of the more common environmental parameters which are probable sources of error are temperature, pressure, acceleration, vibration, supply voltage and electromagnetic radiation. To establish confidence in the ability of a particular instrument to accurately perform its designated task, an understanding of the effect of these environmental parameters is essential.

The reason for making an environmental calibration can be threefold:

- To verify that built-in correction features, such as temperature compensation, are functioning properly according to the manufacturer's specifications.
- To establish that the environmental effects are negligible.
- To determine the sensitivity of the instrument to the environmental parameter in order to provide information for the correction of the measurement results.

In this latter case it must be recognized that a separate measurement of the environmental parameter during the flight test is necessary in order to apply the correction.

Naturally, not every calibration of an instrument requires actual environmental testing of all or even any of the extraneous parameters which may be encountered, but certainly they must be given consideration. The actual flight test environment, prior evaluation tests, previous experience or an understanding of the construction of the instrument may provide the confidence needed to negate the requirement for actual tests as discussed in Section 7.2.2.

As a general rule, the sensitivity of an instrument to environmental parameters is much less than the sensitivity to the primary input. Therefore the accuracy with which these parameters must be generated is generally less than for the main input.

Before setting up a calibration program for environmental parameters, the calibration engineer must have a very good understanding of the construction and operation of the instrument under consideration and the environment to which it will be exposed. The nature of the effect of an environmental parameter on the calibration will depend on the type of instrument. For instance, variation of the supply voltage or the temperature may cause a zero shift without a change of sensitivity, or a change of sensitivity without a zero shift, or a combination of both. Unless the calibration engineer has a good understanding of what type of effect will occur, it is advisable to make a complete calibration of the instrument at several values of the environmental parameter. The test equipment must then make it possible to vary the nominal input parameter and the environmental parameter independently of each other. For analyzing the effect of supply voltage this is generally very simple, but for other combinations of parameters quite complex equipment may be required. Examples are vibration generators which can be tilted with respect to the vertical, in order to test cross-coupling effects in accelerometers; vibration generators which can be subjected to different temperatures for determining the effect of temperature on damping characteristics of accelerometers; pressure connections to temperature chambers so that a pressure instrument in the chamber can be connected to a pressure standard, etc.

7.7 THE OVERALL CALIBRATION OF A MEASURING CHANNEL

The ultimate purpose of the calibration program is to provide the information needed to convert the measuring results to engineering units and to provide a basis for a final check on the accuracy of the measurements. For both purposes the overall (end-to-end) calibration of each measuring channel must be known.

In modern flight testing such overall calibrations of the channel are usually not made directly. They are usually determined from a mathematical combination of calibrations of the components of the measuring channels. There are two main reasons for this procedure. One is that a new complex overall calibration of many channels may be required if one single component, for example an analog-to-digital converter used for many channels, has to be replaced. If the concept of component calibrations is used, only a calibration of this single unit will be necessary. The second reason is that an overall recalibration of one channel may require that a large part of the total data collection system is transported to the calibration laboratory, with consequent danger of damage to some other components. If the overall calibration is performed in the aircraft, less accurate transportable standards will have to be used and other work on the aircraft will be retarded.

Under some circumstances, however, the individual component calibration is either impractical or impossible, and an overall calibration of the complete measurement channel from transducer to recorder or telemeter output is necessary. This is the safest method of calibration because it will include, for instance, the effects of mismatches between adjacent components in the measuring chain or interference between one component and another which may not be found if each component is calibrated separately. In cases where some form of feed-back between separate components or the aircraft structure (such as a control surface) must be included, an overall system calibration becomes a necessity. In some cases the total system may be assembled in the calibration laboratory while in other cases it is obvious that the calibration must be performed on the aircraft after final installation.

The <u>combination of component calibrations</u> into an overall calibration of one measuring channel requires careful consideration. The combination of static calibrations involves multiplication of the input-output ratios corresponding to each calibration point of the physical input parameter, after all necessary corrections for environmental effects have been applied. When dynamic effects are of interest, the amplitude characteristic with the lowest break frequency will mainly determine the overall amplitude response of the measuring channel. The phase response of the other components may, however, affect the overall phase shift characteristic of the measuring channel. In-flight checks or "calibrations" to establish certain environmental effects such as aircraft supply voltage or shifts in FM center frequency may also be considered within the scope of the determination of the overall calibration.

In all overall calibrations calculated from component calibrations there is a possibility that some effect in the actual circuit has not been taken into account. This may be an additional resistance due to a bad connection, an error in the wiring (e.g. the inversion of two connections), an unforeseen grounding point, input impedances different from those used during calibration, wiring capacitance, etc. It is, therefore, necessary to check at least once the overall calibration. This is usually done during the final testing of the data collection system after it has been mounted in the aircraft. The extent of this check must be carefully planned. In many cases a check at a single point may be sufficient, if the engineers are sure that every precaution has been taken. A two-point check or even a full calibration will give additional assurance, but may be more difficult to realize (see also Section 8.4).

The <u>preflight and postflight checks</u> can be regarded as special types of calibrations. Their main purpose is to make a quick or last-minute verification of the correct functioning of all channels. However, they cannot be considered a substitute for normal calibration but are additional to it. The emphasis, here, is on checking the weak points of the measuring system.

7.8 REFERENCES

1. W. Bentley, J. Walter — Transient Pressure Measuring Methods Research, Princeton University, 1963
2. J. Hilten, P. Lederer, J. Sethian — A Simple Hydraulic Sinusoidal Pressure Calibrator, N.B.S. Technical Note 720, Superintendent of Documents, Washington, D.C. 20402
3. T. Beckwith, N. Buck — Mechanical Measurements, Addison-Wesley, Reading, Mass.,1961
4. J. Favour, R. Stewart — Primary Calibration of Pressure Transducers to 10,000 Hz, Instrumentation in the Aerospace Industry, Vol. 15, ISA International Aerospace Instrumentation Symposium, Las Vegas, Nevada, May 5-7, 1969
5. J. Favour — Calibration of Accelerometers by Impulse Excitation and Fourier Integral Transform Techniques, 37th Shock & Vibration Bulletin, January 1968, U.S. Naval Research Laboratory, Washington, D.C.
6. R. Bracewell, — The Fourier Transform and its Application, McGraw-Hill Book Co., N.Y. 1965
7. S. Goldman — Frequency Analysis, Modulation and Noise, McGraw-Hill, Inc. New York 1948

CHAPTER 8

TECHNICAL ASPECTS IN THE DESIGN OF MULTI-CHANNEL DATA COLLECTION SYSTEMS

by

H.L. Tollisen and R.L. van der Velde

8.1 INTRODUCTION

In Chapters 3 to 7 aspects of the design and calibration of single measuring channels have been discussed. In actual flight test instrumentation systems a number of such measuring channels are combined. The number of channels can range from about five for a simple ad-hoc test to several thousands for prototype tests of large and complex aircraft. In this chapter a few of the problems of the design of multi-channel systems will be discussed.

After the test objectives have been specified and a first measurements list has been compiled (see Chapter 2), the basic outline of the instrumentation system must be decided upon. This must be done in close co-operation between management, flight test engineers, data processing specialists and instrumentation engineers. Aspects of this phase are discussed in Section 8.2. When the main components have been defined, the system must be designed, built and prepared for installation in the aircraft (Section 8.3). During this phase numerous tests must be executed as the system takes shape. An outline of such tests is given in Section 8.4.

In the design of a flight test instrumentation system, and especially of the airborne data collection system, two sets of (often conflicting) requirements play an important role. On the one hand there are the requirements for each individual measuring channel, as they have been discussed in Chapters 3 to 6. On the other hand, there is the requirement that all these individual channels must be combined in one data collection system, which can be installed in the aircraft, which can be maintained and which provides the best possible input format to data processing facilities. The specification of a multichannel data collection system must be developed by an iterative process, in which the requirements for the individual channels and the requirements for the total data collection system are weighed against each other until an acceptable compromise has been reached. In the ideal case the resulting compromise will be a single data collection system, for instance a digital system with a certain scanning rate. Often, however, the requirements for the accuracy and frequency response of the individual channels show such a large variation that a system of one type is not feasible. Then a digital system may have to be combined, for instance, with an analog system in order to accommodate a number of high-frequency channels. Such composite systems need not be completely independent: often the digital and analog data can be recorded on different tracks of the same tape recorder and the power supplies and test facilities for both parts can be integrated.

At a lower level similar compromises must be made. In digital systems some individual channels may require their own analog-to-digital converter, but it will often be possible to commutate many of the analog signals and digitize these consecutively by the same converter. Sometimes the flight test instrumentation system can be connected to transducers already available in the aircraft for the normal aircraft systems. Although this is attractive from several points of view, it can only be done if these transducers and their associated circuits are accurate enough for the flight test purposes and if adequate measures can be taken to ensure the integrity of the essential aircraft systems even if a failure in the flight test equipment should occur.

No simple rules can be given for these and many other problems with which the instrumentation engineer is confronted when designing a flight test data collection system. It is his task to select the best compromise for satisfying the requirements of a given test program within the limits of the available resources.

Reliability and accuracy are the leading considerations in the choice of the components and in the design of the system and its wiring. Reliability also affects the design in another way, i.e. test and maintenance facilities must be incorporated in the design so that these operations can be done quickly and efficiently. However, reliability and accuracy not only depend upon the quality of the design and the installation, but also very heavily on the capability and experience of the people who maintain and operate the system. The selection and training of these people, who have to work under

unfavourable circumstances in flight and on the ground and often under heavy pressure, can have a large influence on the success of a data collection system.

8.2 SYSTEM CONCEPT

8.2.1 System modification versus new development

From the standpoint of economics and lead time, it is generally more desirable to update an existing system than to develop a new one. An important aspect is that considerable experience will be available on the characteristics - and the weak points - of the existing system. However, certain aspects of the existing system must be compatible with the new requirements. Such characteristics as size, weight and capacity are more or less fixed and cannot be changed.

Other characteristics of an existing system can often be modified. New transducers and signal conditioners can be incorporated. Sampling rates, frequency response and accuracy can often be increased to a certain extent. Sampling rates can be increased or decreased by techniques such as supercommutation and subcommutation. Higher frequency response can be obtained for continuous-trace recorders by using faster galvanometers and higher paper speeds, and for FM systems by using higher sub-carrier frequencies and higher tape speeds. If the basic system is accurate enough for most of the data but a few high-accuracy data channels have to be included, so-called encoding methods such as coarse-fine techniques can be used.

If the test program is relatively small and the data flow time is not critical, the use of photo-panel or continuous-trace recording may be adequate. All equipment associated with these systems is highly developed and available commercially at reasonable prices. If a computer-centered ground station is available, the use of tape recording should be considered even for small tests. The higher costs of the preparation of the equipment, of the installation in the aircraft and of computer programs will often be outweighed by the advantages of automatic processing, such as shorter turnaround time, less manhours for data processing and better presentation.

Though most systems have a considerable growth potential, it may be necessary to develop a new system for a particular test program. A significant factor in this decision will be the short-range and long-range financial support that can be obtained. If facility funding is available and there appears to be a continuing need for test data, an automated system should be given serious consideration. This is a business matter at best and may also touch on political aspects. Either way, its importance should not be underestimated. Long-range planning of future flight test programs plays an important part. There is often considerable benefit in using the main components of a future complex system for the first time in a relatively simple test, if possible in parallel with a proven system. This may forestall many problems which could affect reliable operation of the complex system.

8.2.2 Choice of the major components

An important decision that must be made before the instrumentation system for a major flight test program can be specified, is whether on-line data processing will be required. On-line processing can, in principle, be applied in two ways:

- on-line processing of only a few parameters and only during flights where considerable benefit can be derived from it, in order to decide in real time whether a test has succeeded and a next test can be executed during the same flight
- on-line processing of all data, so that a complete analysis of the results is available by the time the aircraft lands.

The first method has been in use for a long time. It has been found that the flight time and the number of flights required for testing advanced aircraft can be considerably reduced if a number of important parameters can be continuously observed in real time by specialists. In present systems this has been achieved by telemetering these data to the ground, where they are displayed on CRTs after on-line processing in a computer, but systems using on-board computation and display are also being considered. The need for such a system should be stated early in the development program, as it will have considerable effect on the general layout of the instrumentation system.

The second method, i.e., on-line processing of all data, may be technically possible using telemetry and a powerful ground computer station. This approach is being attempted in some programs

at the present time. It would seem, however, that this approach will, in general, not be economically justifiable and it can be expected that off-line data processing methods will continue to be used as the principal method.

The measurements list (Chapter 2) defines the characteristics required of each individual measuring channel. On the basis of an analysis of all these requirements and of the equipment available on the market, it will then have to be decided whether they can be handled by one system or whether a composite system is necessary, what kind(s) of system(s) will be used and which parameters will be handled by each system. Eventually a choice will have to be made from (a combination of) the following possibilities:

- on board recording (for details see Chapter 9)
  - photo panel
  - trace recording
  - magnetic tape
    - analog
      - FM
      - direct
    - digital
      - computer compatible
      - non-computer compatible
- telemetry (for details see Chapter 10)
  - analog
  - digital
- on-board cameras or closed-circuit television for the observation of external events (flow patterns, external store release, ice accretion)
- on-board cameras for photogrammetric measurements (aircraft trajectories, position fixing)
- ground based equipment (photo theodolites, radar, telemetry ground station, etc.) (for details see Chapter 11).

Except for small single-purpose tests, it is almost inevitable that more than one type of data collection system will be used during a flight test program. The unique capabilities of each system and the broad spectrum of requirements usually make it impossible for one system to handle all the data. For a typical flight test program a <u>composite data collection system</u> may be required which involves the simultaneous use of the following systems:

- a digital system for basic airplane and engine performance data
- an FM system for vibration and acoustic survey
- fuselage-mounted cameras for recording wool-tuft patterns on the wing
- a continuous-trace recording system for quick-look purposes
- photo theodolites for trajectory measurements during take-off and landing tests.

Details on most of these systems are given in Chapters 9 to 11. A few words can be said here about the application of cameras. Film or photo cameras are used for flow investigations with wool tufts, investigations on the shape of ice formations on the wing, control surfaces and engine intakes, measurements of wing and fuselage bending, observation of external store release, etc. Closed-circuit television is also used for some of these tasks, either for real-time monitoring by observers in the aircraft or for play-back after a flight. Photo cameras are also often used for the measurement of aircraft trajectories, both from the ground (photo theodolites) and from the aircraft as in some methods for take-off and landing measurements.

8.2.3 On-board recording and/or telemetry

One of the first choices that must be made is whether telemetry or on-board recording will be used, or both. It can be said that at present on-board recording is the standard method of data collection for most types of flight tests. Even if telemetry is used during part or during the whole program, the data will, in most cases, also be recorded on board the aircraft. The choice of telemetry is based on one or more of several specific reasons. The most important are:

- hazardous flying, such as high-speed and flutter testing to expand the operational envelope of an airplane. This requires evaluation of data on each condition before going to the next, without exposing the crew any more than necessary to the hazardous conditions. Telemetered data available

on the ground makes possible the participation of qualified specialists in critical decisions. The data is also protected in the event of an accident. In this type of testing, only a limited number of critical parameters need be telemetered.

- testing of a small vehicle. The fact that a telemetry transmitter usually is much smaller than a recorder with adequate data capacity m lead to the choice of a telemetry system.
- on-line processing of telemetered data. This has been discussed in Section 8.2.2.

Telemetry has, however, certain disadvantages:

- the aircraft must be operated within "line of sight" of the receiving antenna. This may seriously restrict the area in which flight tests can be made. The signal-to-noise ratio should be monitored continuously on the ground.
- the radio link is susceptible to interference from other transmitters and may deteriorate due to adverse atmospheric or ionospheric conditions. The resulting loss of data can have a very serious effect on the progress of the flight testing, especially if on-line processing is used. For this reason on-board recording is generally used as a back-up.
- the total system is more complex and therefore more liable to malfunctioning. System checking is more complicated for this reason and also because it must include both the airborne and the ground equipment, and the radio link between them.
- data security is compromised because others can also receive the signal.

Detailed discussions of on-board recording and telemetry are given in Chapters 9 and 10.

If the use of telemetry is envisaged, the parameters to be transmitted must be selected first since this can have a considerable impact on the choice of the on-board data acquisition equipment. In many cases the most economical solution is to use the same data acquisition electronics for recording and telemetry.

In many flight test programs there is a requirement for protection of at least part of the flight data in the case of a crash. As mentioned before, this can be done by telemetry. If no telemetry is available, crash-proof containers can be used for the recording medium. This approach can be used for cameras, magazines of continuous-trace recorders and for tape recorders. In some cases a separate crash-recording system is used, for instance, with a wire recorder or one of the commercially available airline-type crash recorders. These have, however, usually a limited data recording capacity.

8.2.4 Methods of on-board recording and telemetry

Analysis of any set of parameters will show that a division into three main categories can be made with respect to required frequency spectrum and accuracy:

- low-frequency data (up to about 5 Hz); for some of these data a high accuracy may be required (e.g. 0.2 % FS), but for other low-frequency data a high accuracy will not be important
- medium-frequency data (up to about 30 Hz); for this type of data an accuracy of about 1 % FS will usually be sufficient
- high-frequency data (up to several kHz); for these data a relatively low accuracy (2 to 5 % FS) is usually acceptable.

The first two categories are suitable for digital systems, and the third is usually handled by analog systems. If for a few parameters the required accuracy can not be obtained with an available digital system, coarse-fine recording should be considered on two channels per parameter. In the case of a high-capacity system it may be possible to accommodate high-frequency parameters by cross-strapping a number of input channels, i.e. supercommutation (Chapter 10).

Digital tape recording is now generally the backbone of all large flight test programs. In recent years the use of digital data collection systems has increased enormously. There are two principal reasons for this:

- since analog-to-digital converters are relatively inexpensive and bit packing densities can be quite high, it is more efficient to do the digitizing on board the aircraft.
- as soon as the signal has been digitized, there is no further loss of accuracy during the data

manipulation, transmission and storage. Digital recording and telemetry are therefore especially suitable for high-accuracy data.

At first thought it would seem to be advantageous if the tapes made on board the aircraft could be read directly by a standard digital computer, i.e. if the on-board recorder produced a computer-compatible tape. In practice, this is hardly ever attempted. The main reasons for this are:

- the tolerances of standard digital computers with respect to bit density and skew are so close, that even good flight recorders often cannot remain within these tolerances when subjected to the linear and angular accelerations normally encountered during flight tests.
- standard digital computers require half-inch tapes with data recorded in parallel on either 7 or 9 tracks at closely specified bit densities. At the bit densities achievable in airborne parallel recording, the number of data points per tape is relatively low. In order to achieve a better utilization of the tapes, other formats are often preferable, for instance 1 inch wide tapes with 14, 16 or 31 tracks or serial recording with extremely high bit densities.
- standard digital computers require "inter record gaps" after a certain number of data words. During these gaps no data must be recorded. The flight test data are, however, generated continuously. Some kind of buffer storage is then required which involves a considerable increase in the complexity of the airborne equipment. An alternative is to interrupt the data stream during the generation of inter record gaps, but then valuable data may be lost.

Because in most data preprocessing stations a special computer is available for quick look and editing, it is generally possible to use this computer also for converting the flight tapes to a computer-compatible format.

Analog data collection systems are primarily used for recording high-frequency signals. Interpretation of these data is often more conveniently done using traces showing the time histories of the measured parameters. Analog tape recording can also be more convenient if analog data processors are to be used, as for instance in some types of frequency analysers. Although analog signals can be reproduced on the ground from digital recordings, it is usually more costly to do so.

Analog systems can produce continuous data or sampled data, digital systems always produce sampled data. Analog sampled data systems include photo panels, and pulse-amplitude modulation (PAM) and pulse-duration modulation (PDM) methods. Continuous-trace recorders and direct-recording tape recorders produce continuous data. Frequency modulation is on the borderline between the two types: the signal is "sampled" at a rate varying with the instantaneous signal amplitude. For all sampled systems it must be kept in mind that the sampling frequency must always be higher (and often appreciably higher) than the highest frequency which is of interest for the measurement, in order to reduce the effect of aliasing errors (see Chapter 6).

The advantage of analog tape recording over trace recording and photo panels is that the signals can be reproduced in electrical form when the tape is replayed. This makes it possible to use automatic or near-automatic data processing, including digitizing on the ground. Direct recording and FM modulation techniques are generally used for analog tape recording and, after modulation on an RF carrier, also for telemetry. These modulation techniques are described in Chapters 9 and 10.

Combinations of different systems using the same tape recorder can be very efficient. PCM and FM data can be recorded on different tracks of the same tape recorder as long as there is a suitable tape speed for both systems. There may, however, be objections to this from the data processing people, especially if both types of data have to be processed simultaneously at different locations.

Photo panels are still used occasionally because of their extreme flexibility (which is an important advantage in small ad-hoc tests) and because many types can be used for visual monitoring during the recording.

Continuous-trace recorders can record up to 50 parameters at moderate cost and are very useful and popular for the recording of dynamic data, especially if the measurements involve the phase

relationship between two or more variables. Galvanometers are available to handle data frequencies up to 1000 Hz or higher. Their accuracy can be of the order of 1 to 2 percent. This type of recorder is very useful for those types of tests where the interpretation can be made directly from the recorded time histories. If further data processing is required, the traces must be processed manually. Although some equipment is available for assisting in this task, it still involves much human labour for all but very short and simple tests.

8.2.5 Data processing aspects in the design of a data collection system

During the design of the data collection system the instrumentation engineers should be aware of the data processing methods which are to be used. A well designed data collection system can markedly reduce the expensive time required for final data processing. In this section a few examples will be given of how the designer of the data collection system can simplify the data processing.

The most direct method is to do data processing operations on board during flight. This can be done using an airborne computer, as described previously. But even if no computer is used, many operations can be executed in the data collection system which would otherwise have to be done during data processing. A simple example is the on-board determination of the ratio between the transducer output signal and the supply voltage for those transducers whose output is proportional to the supply voltage. On-board compensation for environmental effects can also be included in this category.

Time correlation and interpolation calculations can be reduced considerably by a judicious design of the data collection system. If the time correlation between two signals is of interest, they should be recorded in the same recorder on tracks which can be read simultaneously. The channels should be designed so that they have identical amplitude and phase characteristics. These are not only determined by the transducer and signal conditioning characteristics, but also by those of the recording method. In the case of continuous-trace recording the dynamic characteristics of the galvanometers should be as nearly as possible the same, in FM recording they should be recorded on the same carrier frequency. Interpolation of digitally recorded data can be avoided if parameters for which time correlation is important are sampled in consecutive time slots.

In-flight reduction of the quantity of data recorded will decrease both the required recording capacity and the data processing time. Several methods can be used:

- recording only during the significant stages of the flight.
- recording only those channels which are of direct interest to the test. The data channels required for each flight are then selected by a patch panel or a program control (see Fig. 8.3).
- adapting the sampling rate to the nature of the tests and changing the tape or paper speed accordingly.
- using data compression methods, i.e. data are recorded only when they have changed by more than a specified amount. This requires additional identification on the tape of the channel and of the time at which the change occurred. It will only be beneficial if the average intervals between such changes are much longer than the sampling interval and if accurate knowledge about their rate of occurrence is available before the flight. Data compression is as yet rarely used in flight testing.

There are several reasons why these methods for reducing the quantity of recorded data are not often used in flight testing. The first reason is that unforeseen events may not be recorded. A second reason is that the opportunity to extract useful data from all flights is lost (see Chapter 1, Section 1.3.1.1, fourth paragraph). A third reason is that the manufacturer of the specimen being tested will normally like a complete history of all parameters during the testing period.

If the on-board recording capacity is sufficient for recording all data channels throughout the flight, it is possible to reduce the quantity of data to be processed by editing on the ground. This can be facilitated by recording additional information such as measurement number, frame number, time of day or elapsed time, and by using event markers to record the occurrence of special events.

8.3 TECHNICAL DESIGN AND DEVELOPMENT CONSIDERATIONS

8.3.1 Introduction

At a certain point of time the system concept has been sufficiently finalized after discussions among aircraft designers, flight test engineers, data processing specialists and instrumentation engineers to permit the initiation of the detailed development of the new components. It should be realized that all future possibilities are determined by the constraints of these choices.

The design of the individual channels has been discussed in some detail in Chapters 3 to 6. Some general and organizational aspects have been dealt with in Chapter 2. It is the intention of this chapter to discuss, in general terms, some topics relevant to the design and development of a complete system and also to discuss some of the problems which arise when the constituent parts of an instrumentation system are brought together (integrated) and when the complete instrumentation system is installed in the test aircraft. Some of these interface problems will be dealt with in separate sections.

As a cautionary note, instrumentation engineering has progressed a long way in the last few years. Attempts to "connect a few components together" will almost surely result in a system that is inadequate for even the most rudimentary measurements. Adequate attention must be given to inter-element effects, including impedance matching, frequency response, ground loops and shielding. The analytical determination of overall system operating characteristics requires an intimate knowledge of the detailed, quantitative descriptions of the characteristics of each element in the system. Instrumentation engineering is a profession and a well-equipped, trained and experienced team is an absolute requirement for the successful completion of a flight test program.
The range of requirements of the various programs and system capabilities are so diversified that it is very difficult to buy a complete, off-the-shelf system that satisfies all needs of a particular flight test program. As a consequence, program requirements are met in one of three ways, depending upon the in-house resources and capabilities available:
- the complete design and construction is done in-house
- the components are procured and their integration is done in-house
- the complete system is procured on contract.

Except for the number of people required, the involvement of the user's organization is about the same. Even if the total system is procured, competent staff is needed to prepare the detailed technical specifications, monitor the design and construction phases, and, after delivery, perform acceptance tests and then maintain and operate the equipment.

8.3.2 Commutation and normalization of input signals

For data collection systems which do not use commutated data, such as continuous-trace recording systems and systems using single-channel FM, each channel can more or less be designed separately. The main constraint is that all channels have to be recorded at the same recording speed. For data collection systems with commutation the general layout of the commutation system must be determined at an early stage in the design.

The basic principles of commutation (multiplexing) are described in Chapters 9 and 10. In systems with frequency-division multiplexing the main concern is to divide the channels over the available (sub)carrier frequencies so that each channel obtains its best frequency response. If the frequency spectra of all channels are similar, a constant-bandwidth system will often provide optimal results. If the spectra of the signals differ and a few of the channels have frequencies above about 300 Hz, a proportional-bandwidth system must be used.

Most modern flight test data collection systems mainly rely on time-division multiplexing. This is used in all digital and PDM systems, and can be used in FM and direct recording and in FM and AM telemetry. The first step in designing such a system is to determine the required basic commutation rate. This is, in principle, the highest sampling rate required for any channel, though super-commutation may be used if a few channels require a higher sampling rate than all others. It must

be stressed here again that the required sampling rate is always higher than the frequency range mentioned in the measurements list. It is determined by the acceptable aliasing error in the channel. The methods to determine the required sampling rate for a given frequency spectrum are described in Chapter 6.

When the basic commutation rate has been fixed, the number of measurements per commutation cycle must be determined. As discussed in Section 8.2.5 it is often possible to reduce the required number of channels by selecting only those which are essential for a particular flight by means of a patchboard. The number of measurements per cycle is determined by the highest number of channels required on any flight and by the amount of supercommutation and subcommutation required.

The basic commutation rate and the number of measurements are primary factors determining the design of the data collection system. They not only determine the commutation speed itself, but also the speed of the analog-to-digital converter and the signal conditioning units. When designing a new system, they should be considered very carefully because they have a large influence on the growth potential of the system.

The basic commutation rate is an important factor in the selection of the type of switches used in the commutator. As described in Section 5.3.4 (Chapter 5), normal relays or reed relays can be used at low commutation rates, but electronic switches must be used if the basic commutation rate is above 100 to 200 samples/sec. At the present state of the art, electronic switches are often also used at lower commutation rates, even for low-level signals. Electronic commutators are extremely versatile and can be made very small as several switches can be incorporated in one integrated circuit. Their design requires a few precautions. The impedance of the switches in the closed condition is not very low (in the order of 1000 Ohms) and they produce a small leakage current in the open position (in the order of 10 nanoamperes). In a properly designed circuit these characteristics will, however, hardly affect the measuring accuracy. Cross talk, i.e. changes in the signal level of one channel caused by the signal level in another channel, can cause difficulties, especially when integrated circuits are used with many switches. This problem must be solved by proper grouping of the input channels. Relatively large back currents, which can cause damage to the signal sources being sampled can occur due to breakdown of the switches themselves or of the circuits behind them. Series resistors are often necessary to limit these currents. Notwithstanding all these effects, good results can be obtained with well-designed electronic commutators, even with low-level signals.

When the basic commutation rate, the number of measurements per cycle and the type of switches have been selected, the general layout of the data collection system can be planned in more detail. An important factor is at what stage the signals are commutated. The most straightforward method in a digital system with analog inputs is to place the commutator directly before the analog-to-digital converter (Fig. 8.1). Then each channel has its own signal conditioner, which transforms the transducer output signal into the type of signal required by the analog-to-digital converter. This is usually a DC signal, either high-level (e.g. 0 to 5 Volts) or low-level (e.g. 0 to 30 mV). Other types of input signals have been used in the past (for instance PDM signals), but these are not very common nowadays.

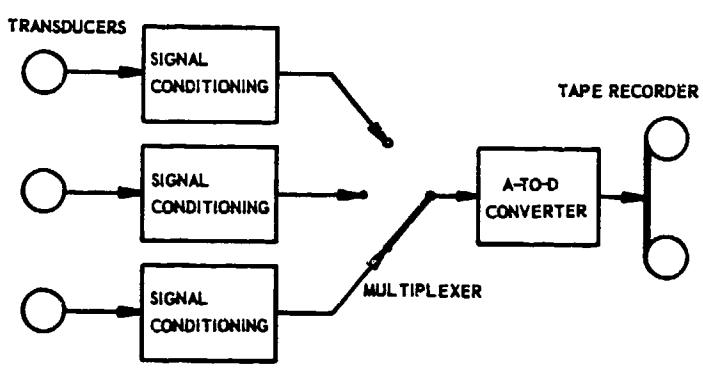


Figure 8.1 Data collection system with separate signal conditioners

In the system shown in Figure 8.1 the signal conditioning circuits are not applied in a very economical fashion, as each one is only used during a very brief time period of each commutation cycle.

Therefore, a common signal conditioner is often used for all signals of the same type. A simple example of such a system is shown in Figure 8.2. The multiplexer connects the signals from transducers with

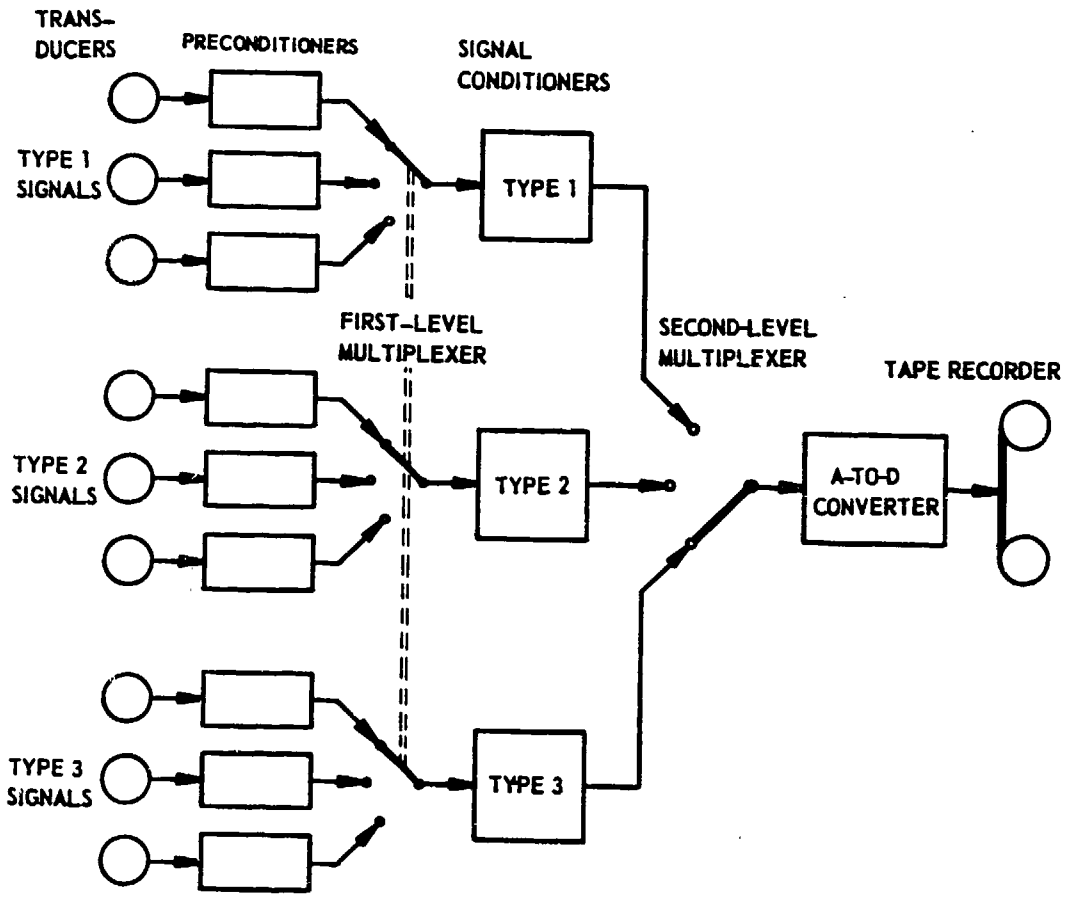


Figure 8.2 Data collection system with common signal conditioners

the same type of output to the associated signal conditioner and thus the number of signal conditioners is equal to the number of types of signals. As this number may still be quite large, simple "preconditioning" circuits are sometimes provided to further reduce the number of signal conditioners. These preconditioners can include filters for individual channels, cold-junction compensation for thermocouples, amplifiers or voltage dividers which adapt the electrical range of the signal, etc. The final choice of what should be included in "preconditioning" and what in "conditioning" will depend on the number of transducers of each type.

The system of Figure 8.2 still has the disadvantage that each commutation switch is connected to a predetermined signal conditioner and that, therefore, the possibilities of replacing a transducer by one with a different type of output are limited. In large modern flight test systems this limitation is overcome by using a computer or a programmable memory for controlling the commutation cycle. An example of such a system is shown in Figure 8.3. The sequence in which the channels are scanned, and the scanning rate of each channel, can be programmed separately for each flight. The single central signal conditioner will be adapted to each incoming type of signal by the program control.

In each system there are a number of channels which cannot be handled by the normal commutation system. This is, for instance, the case for those pulse-rate or frequency signals whose period is much longer than the sampling time available for each channel (for example, engine tachometers and fuel flow meters). The measurement of such signals must have a duration of at least two periods of the lowest frequency that can occur, and integration over a still longer period may be required. Such channels must have a separate analog-to-digital converter, which is sampled by the second-level

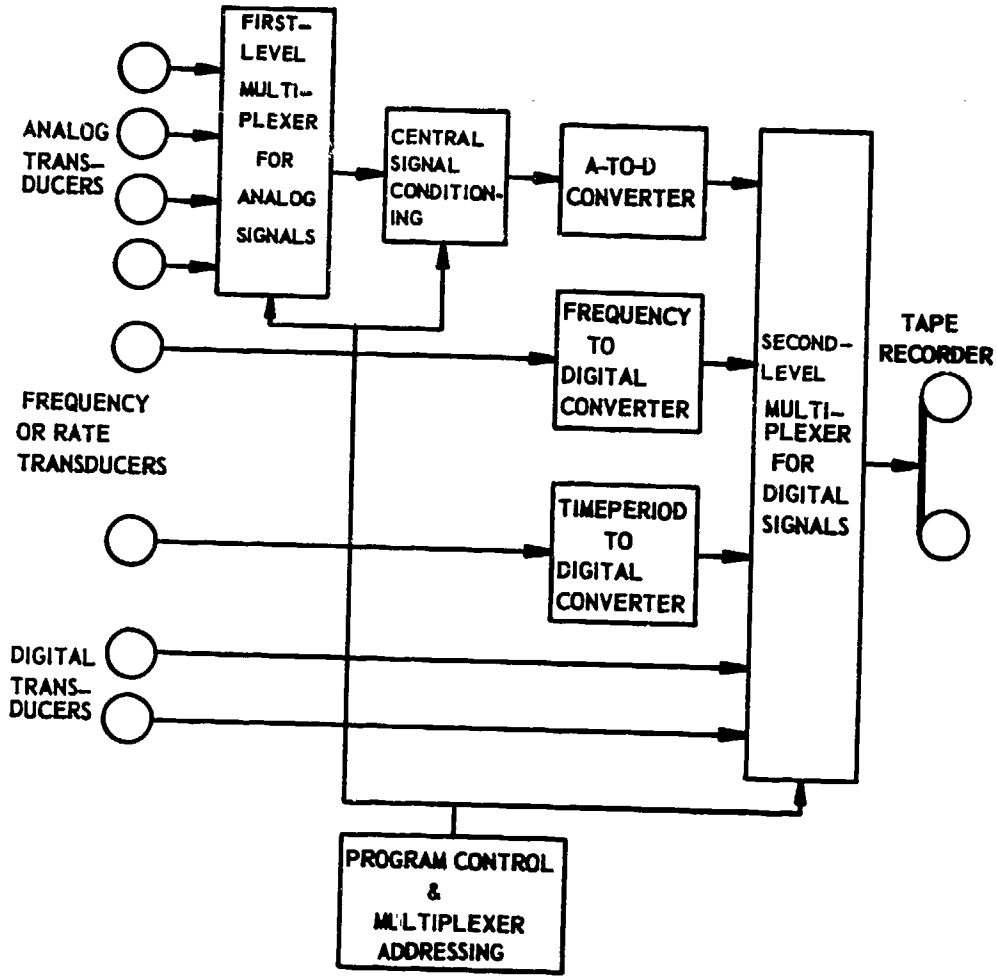


Figure 8.3 Data collection system with computer-controlled commutator and signal conditioner

multiplexer, as shown in Figure 8.3. Signals which already have the digital format are also scanned directly by this second-level multiplexer.

For large and complex flight test systems the weight of the wiring for instrumentation can become prohibitive. This weight can be markedly reduced by remote multiplexing. Several systems like that of Figure 8.3 are then mounted at locations in the aircraft where large numbers of transducers are concentrated. They are controlled by a single program control unit. The digital output of each remote multiplexing unit can then be transmitted to the recording system by a single pair of wires and only relatively few wires from the central program unit to each remote multiplexing unit are required.

8.3.3 Maintenance and performance monitoring of the data collection system

Maintenance and performance monitoring are required to prevent and to correct failures and performance degradation. The overall flight test schedule must allow specific periods for routine checkout and maintenance of the instrumentation system.

During the design phase measures must be taken to prepare for maintenance and performance monitoring. Test connections necessary for a quick and efficient maintenance must be carefully planned. It is very difficult to determine in advance precisely what will have to be checked and where the weak points of the system are. Experience and familiarity with the performance of the components will provide a good basis for determining what test points must be available and what test procedures must be used. As systems often give problems at points where they were not expected, it is advisable to design the maintenance system so that every conceivable function can be tested. During the operation it will be found which checks can be omitted or can be done at longer time intervals. It is, however, very difficult to add test points or test equipment during the operational phase.

Closely related to maintenance is the aspect of performance monitoring, either on the ground or in flight. The requirements for special equipment for performance monitoring on the ground during preflight and postflight checks depend on the time available between flights. Less time between flights means more sophisticated checkout equipment. Even completely automatic ground checkout systems (generally referred to as ATE, Automatic Test Equipment) have been considered for flight test instrumentation systems. Though ATE is used with success for checking operational aircraft and large missiles where the test sequence has been precisely defined, it is less suitable for flight test purposes. During the course of a flight test program many parameters have to be changed and even more drastic modifications are often required. When making these changes it would also be necessary to modify the ATE. This increases the time required for making changes and tends to defeat the purpose of the ATE. ATE is, therefore, seldom used in flight testing.

A valuable aid for monitoring the performance of the instrumentation equipment is BITE (Built-In-Test-Equipment), which is often incorporated by the manufacturers of major component parts. BITE, however, only tests the functioning of that specific component. Efficient overall monitoring of tape systems can be achieved by the "read after write" method, i.e. the data is read from the tape immediately after recording. This data can then be displayed directly or can be used to check parity, code, timing, level, etc. A simpler method, which provides only slightly less coverage, is monitoring the data stream to the recorder write heads. Another effective technique is the use of calibration signals. Comparison of the measured values with the known calibration input values provides a fairly comprehensive check of the data acquisition process.

In-flight performance monitoring should be seriously considered. Both from a standpoint of instrumentation checking and in-flight data interpretation it is desirable to be able to monitor in flight at least some of the measurements being recorded. In most cases, some level of monitoring soon becomes cost effective, because valuable flight time can be saved in case of a failure in the instrumentation equipment. The complexity of monitoring and the method of presentation depend on the attention which can be provided by the flight test crew. In a one-pilot aircraft a single go/no-go light is about the maximum that can be allowed. This light can, however, be the output of a comprehensive self-check system. In an aircraft carrying flight test observers the necessity for such a fully automated system is less, as there is much more opportunity for improvisation. Even on-board repairs may then be feasible.

8.3.4 System Integration

8.3.4.1 Integration of main components into a complete system

For the part which is common to all channels the main components (commutators, analog-to-digital converters, modulators, recorders, telemetry transmitters etc.) are usually bought as complete units. They are available in a relatively large variety from specialized manufacturers. If special requirements exist which cannot be satisfied by commercially available units, these manufacturers can usually modify standard equipment to provide acceptable performance. If the different modules have not been especially designed to be used together, interface problems may occur even though the specifications seem to indicate that the output characteristics of one unit are matched to the input of the other unit. This is mainly because specifications are never complete in all respects. Sometimes characteristics not mentioned in the specifications can be the cause of interface problems. Usually these problems have something to do with radiated or conducted noise, grounding and shielding.

Ample time should be allowed for matching the different modules, transducers, etc, followed by adequate testing. This is especially the case with components obtained from different manufacturers, or if special equipment has been built in-house.

Early in the design stage, a decision must be made regarding the packaging of electronics constructed in-house. There is no need to dwell upon the advantages of standardization in this respect. In small aircraft, however, it may be difficult to adhere to existing standards for equipment boxes and racks. Often ad-hoc solutions will have to be found to mount boxes in small corners.

In systems involving more than one recorder time synchronization between the different recording systems is very important. It is desirable to utilize the same time base and format if at all possible, to simplify data correlation. If this is not possible, as in some non-automatic systems, it becomes

necessary to provide additional event marks on all systems, which can be used for time correlations between the individual time bases of the recorders. When airborne and ground based systems are used simultaneously time correlation may require the use of a radio link, unless the required accuracies are low. The problems of time correlation are discussed in more detail in Chapter 11.

8.3.4.2 Integration into the aircraft

Some factors influencing system design relating to the integration into the aircraft are:
- accessibility
- weight and size of boxes and wiring
- unwanted interaction between instrumentation systems and the aircraft.

Accessibility of the instrumentation equipment is an obvious requirement for maintenance. It is sometimes unavoidable that sensors and cabling are mounted in places which will not be accessible later. They are for instance mounted during assembly of the (prototype) aircraft or during a major overhaul. This must be avoided as much as possible because considerable time and effort will have to be spent, should they become unserviceable.

Weight and size of boxes and wiring can constitute a problem in many aircraft especially in small fighter aircraft. Sometimes it is possible to install instrumentation equipment in locations normally occupied by standard aircraft equipment if this is not essential for the specific flight test. For instance, if armament and ammunition boxes can be removed, much space can become available. Another solution can be to split up the system into several smaller units, for which space can be more easily found. If no space is available inside the aircraft, or if the equipment must be easily exchangeable between aircraft of the same type, the instrumentation system can be installed in an externally mounted pod. In large aircraft a considerable amount of cabling is required to connect all transducers to the instrumentation equipment. Apart from the weight of the cabling, which can become excessive, long signal wires tend to decrease system accuracy. Remote multiplexing, which has been treated in Section 8.3.2, can provide an improvement in both respects.

Unwanted interaction between instrumentation and aircraft systems and vice versa can be caused by faults in the electrical circuits or by electrical noise.

The system must be designed so that faults originating in the instrumentation equipment cannot degrade aircraft systems performance. A fault analysis of the instrumentation equipment should reveal what currents could flow to or from aircraft systems. Measures must be taken to limit these currents to acceptable values.

Electrical noise can be defined as the unintentional and unwanted influence which one electrical circuit can have on another by means of radiation or conduction. The instrumentation system should be designed so that it will not cause interference by radiation or conduction. On the other hand, it should not be susceptible to such interference emanating from the aircraft and its systems. Several civil and military documents give guidance and state requirements regarding this matter (Refs. 5, 6, 7, 8, 9, 10, 13).

Radiation can have a predominantly magnetic or electrical character. A conductor carrying a large current will mainly produce a magnetic field, a conductor with a high voltage will mainly produce an electrical field. In general, it can be said that the higher the frequency, the more problems can be expected from radiation. The effect of radiation can be minimized by:
- shielding
- proper grounding and bonding techniques
- increasing the distance between conflicting circuits
- twisting wire pairs or using coax cables
- avoiding the use of unnecessarily high frequencies and very sharp pulses
- avoiding leaks in radio-frequency transmission lines
- limiting the bandwidth of the instrumentation system as much as possible
- using differential amplifiers to minimize common mode noise.

The routing of wires through an aircraft should be carefully planned to separate as much as possible the susceptible circuits from the circuits which cause interference. In principle three categories of wiring can be distinguished:

- wiring that may cause interference, for instance: power wiring, antenna cables, wiring for the operation of inductive devices, wiring carrying pulsed energy
- wiring that is susceptible to interference, for instance: amplifier inputs, low-level high-impedance circuits
- the category in between, which is neither causing serious interference nor very susceptible to interference, for instance: low impedance wiring, low energy wiring, low voltage power and lighting circuits (except fluorescent lighting).

Wires belonging to different categories should be kept apart as much as possible, unless it has been established that no interference occurs.

Conduction of electrical noise mainly takes place through power leads. It can be minimized using filters, voltage stabilisers, DC-to-DC converters or rotating inverters. In extreme cases it may be necessary to use separate batteries. Some more details are given in Chapter 5 and Sections 8.3.5 and 8.3.6.

8.3.5 Grounding

Ideally, "ground" in an electrical or electronic system is a conductor with zero impedance throughout, which is used for all return currents. In practice, however, small impedances exist in all ground conductors. If several circuits, which are otherwise independent, share a common ground conductor, the current of each circuit contributes to a voltage across that conductor. It is clear that the current from each circuit will affect the currents in other circuits. It is therefore advisable to separate power currents from signal currents whenever possible.

Inside the instrumentation boxes this leads to the use of three distinct types of ground, i.e. power ground, chassis ground and signal ground.

Power ground is used for all return currents from power supplies and loads such as relays, heaters, motors, etc. The power ground must be brought out of the box on a separate connector pin, which must be tied to the aircraft structure with a low impedance lead.

Chassis ground or case ground is a safety ground which connects the metal structure of the equipment to the aircraft structure to protect personnel against electrical shock hazards in the event of a short circuit between a high voltage and the equipment structure. The chassis ground must also be brought out of the equipment on a separate connector pin which must be tied to the aircraft structure by a low impedance lead. If properly designed for that purpose, the cases can also provide radio-frequency shielding. The chassis ground connection must then have a low RF-impedance.

The signal ground is a high quality ground. No return currents from power supplies are allowed through a signal ground, only small signal return currents. In more complex instrumentation systems it is advisable to specify galvanic isolation between the signal ground and the power ground inside the boxes. The power supply unit of the instrumentation equipment must then contain a transformer in which the secondary winding is isolated from the primary. This is normally the case when the instrumentation equipment receives its power from the AC supply of the aircraft. If the instrumentation system receives its power from the 28 Volt DC supply of the aircraft, a DC-to-DC converter which contains such a transformer can provide galvanic isolation between power and signal grounds. The signal ground is also brought out of the equipment on a separate connector pin.

All aircraft electrical power systems use the aircraft structure as a return. This implies that each point of the structure has a different potential, which is not only dependent on currents but also on the resistance of a large number of mechanical joints, which, in spite of electrical

bonding straps, have unpredictable and varying electrical characteristics. The potential difference between two points on the structure may consist of a DC component, a 400 Hz component, switching transient spikes, radio-frequency noise, etc. up to a total RMS-value of several Volts. It is clear that error voltages of this nature cannot be allowed to enter a signal path. This can be avoided by connecting all signal grounds of the instrumentation system with each other and connecting this common signal ground to the aircraft structure at one point only.

In practice this cannot always be realized. In some transducers the signal ground is connected to the case, and the instrumentation system may have to be connected to operational circuits which are grounded elsewhere. Then ground loops occur, which can cause large errors in the signal voltages. This can be avoided by using differential amplifiers (see Chapter 5), where a voltage difference between the input and output signal grounds is rejected as a common mode voltage.

Even if all signal grounds are interconnected and grounded at one point, common mode voltages can occur due to capacitive coupling with the aircraft systems. This can be reduced by shielded and/or twisted wire pairs with properly grounded shields and by using differential amplifiers.

8.3.6 Electrical power

Whenever possible the 28 Volt DC power supply of the aircraft should not be used for instrumentation systems except for the least sensitive devices, such as heaters, motors, etc. This avoids a lot of trouble as the 28 V DC supply is a notorious source of interference. Reference 9 gives a characteristic of its properties. Electric equipment that must be powered from this source should include very adequate voltage stabilization and filtering circuitry. Most aircraft have a three-phase 115/200 V, 400 Hz AC supply which can be used for instrumentation equipment; 28 V DC instrumentation equipment should be powered from the AC supply via a separate transformer-rectifier unit only used for the instrumentation equipment.

If an airborne computer is incorporated in the instrumentation system, special precautions will be necessary to protect the memory during power interruptions or transients. Interruptions of about 50 milliseconds in the AC power supply are quite common during bus transfer in electrical systems. Battery buffering will normally be provided for essential DC busses.

In electrical AC power systems with more than one generator and one bus, two versions are possible:

- the generators have been coupled electrically (voltage, frequency and phase) and are feeding all busses in parallel
- each generator is feeding its own bus and is running independently of the others with its own voltage, frequency and phase.

All these considerations will affect the instrumentation system design. In general, it is best to feed the system from one bus. The system designer should be aware of the possibility of a beat frequency if the generators are not coupled. Furthermore, he should take care that in the case of AC ratio signals the reference voltage is taken from the same phase from the same bus. This also applies to synchro and servo circuits.

It is almost needless to say that the available power source must have adequate capacity to carry all possible simultaneous loads.

8.3.7 Data analysis requirements of the instrumentation engineer

During the design, realization and operational stages, close co-operation between flight test engineers, instrumentation engineers and data processing specialists is necessary. Primary topics of discussion should include:

- project definition in terms of number and schedule of flights
- amount of data and required turnaround time per flight
- definition of flight data formats
- data presentation requirements
- data routines for instrumentation checking
- routines for data processing.

The data processing equipment must be compatible with the requirements of the instrumentation engineers concerning quick look and instrumentation checking (see also Chapter 12).
Typical requirements for a large instrumentation system are:

- quick-look facilities for a postflight instrumentation check which can produce graphs or tables
- facilities for the print-out of selected digital values in the code in which they were recorded (binary, octal, binary-coded decimal or hexadecimal) as an aid in error detection
- capability to observe the signals coming from the read amplifiers of the flight tape playback unit for troubleshooting of the airborne recorders
- immediate access to the preprocessing facility in case of a failure in any part of the instrumentation equipment
- software for instrumentation checking (comparison of in-flight calibration values with the known reference values, counting incorrect parities and other irregularities in the recorded codes, etc.) and for maintenance and development tests such as described in Sections 8.4.1 and 8.4.2.
- access to computer stored calibration files.

8.4 THE TESTING OF INSTRUMENTATION SYSTEMS

8.4.1 Environmental testing

At various intermediate stages during the development and construction of an instrumentation system it is necessary to check the hardware produced so far for proper functioning under the anticipated environmental conditions. General information about the environmental conditions at different locations in aircraft is given in literature (e.g. Ref. 5). The actual conditions must, however, be checked for each specific aircraft. In case of unusual applications or locations of the instruments, for instance, if they are mounted in a pylon tank of a military aircraft, the environmental parameters will have to be measured at the earliest possible moment. Procedures and equipment for environmental tests are described in References 5, 6, 8, 9, 10 and 13. The errors which the environmental conditions can be allowed to produce must be determined from the overall accuracy requirements (see Chapter 7). The environmental conditions can also cause effects which are not directly related to accuracy. Extreme temperatures or vibration can make the operation of certain components so marginal that failures will occur too often. In those cases the instrumentation engineer must decide what can be tolerated.

The objective of environmental testing is to obtain a high degree of confidence in the capability of the equipment to operate within its specified limits in the actual aircraft environment during its entire service life (MIL-STD-810, Ref. 6).

Depending on the application and location of the equipment in the aircraft a choice of the following tests or combination of tests should be considered (some relevant topics are mentioned between parentheses):

- altitude (maximum, rapid decompression)
- temperature (low, high, shock, cycling)
- vibration (resonance search, resonance dwell, vibration cycling, fatigue)
- acceleration (linear and angular, frequency range, amplitude)
- shock
- humidity (condensation, corrosion, leakage paths)
- explosive atmosphere
- rain
- power input (voltage variations, transients, frequency variations, harmonic distortion)
- radio frequency susceptibility (radiated and conducted)
- hydraulic fluids
- sand and dust
- fungus resistance
- salt spray
- acoustic noise.

8.4.2 Functional testing

The realization phase is characterized by a continuous flow of small functional tests and resulting "debugging". The electronic engineers will test the detail circuits they designed. The instrumentation engineers will test the modules and major components as they come in from the manufacturers or from their own workshops.

Printed circuit boards are brought together in boxes. Boxes are connected together and to transducers, recorders, transmitters, cameras etc. Each time a new part is added a functional test should be executed, for, no matter how meticulous the preparations of the specification and fabrications have been, problems are liable to occur. They may arise from inadequate noise suppression, missing ground-wires, capacitive or electromagnetic coupling, self-heating effects, mechanical or electrical tolerances, spurious signals, transients induced in power lines, misinterpretation of specifications, plain mistakes, negligence or poor workmanship.

Integration of a number of measuring channels into a system implies that one channel is physically brought into proximity with others, which may result in electrical interactions. Signals fed to the same multiplexer may interact (cross talk) due to defects or a non-ideal insulation resistance. Residual charges in sample and hold circuits or signal conditioning amplifiers may affect the next measurements.

To check interchannel cross-talk the following procedure can be followed:
Each data channel is provided with a constant input signal, the value of which can be varied. The electrical properties of the signal sources should preferably be identical to the electrical properties of the transducers. The recorder is then switched on and the constant signals of all channels are recorded. Then the input signals are varied, one at a time. The resulting tape can be processed using a special program. For each channel all values which are beyond a predetermined limit from the intended value should be displayed. It is convenient to make histograms or probability distributions for each parameter under specified conditions, which can be used in the determination of the accuracy and can be a reference for similar tests made later.

Another functional test is the determination of system accuracy. The static calibrations of the data channels must be verified repeatedly over a longer period of time and under various environmental conditions, especially temperature and vibration.

It has often been found that a system which performed well under all kinds of tests in the laboratory failed when used under actual flight conditions. There can be technical reasons for this, which are often difficult to predict, but an important factor can be the human element. In the laboratory the equipment is usually operated by engineers closely associated with the development. When it is installed in an aircraft it will be operated by the people involved in the flight test operations. Experience has shown that it is necessary to test as great a part as possible of the equipment in flight before the complete system is finally installed. These flight tests need not be done in the aircraft in which the instrumentation system is to be used. Apart from the technical checks on the equipment, such flight tests provide a very good opportunity for training the people who will have to operate it. It is desirable to make a flight test with the total instrumentation system after its final installation. This may, however, not always be possible, e.g. with prototype aircraft.

8.4.3 Total system check-out in the aircraft

When environmental and functional tests have given sufficient confidence in the system, the complete system is installed and a total system check-out is made. That will provide the basis for a final judgment of the functioning of the total system. It is the last phase before the system is used in the flight test program.

The first step is to check the stability and accuracy of all outputs. Stability checks can be done by recording the data under several conditions and to process them as described for the cross-talk tests in Section 8.4.2. Any instability should be traced and remedied. Accuracy of the channels

which have already been calibrated in the laboratory can be checked by overall calibration checks at one or more points of the measuring range of each input parameter. This is a very important check, and the input stimuli used should be as accurate as possible. Small, but significant, errors may otherwise remain undetected. Such errors can be caused, for instance, by wrong grounding connections, errors due to wrong matching of components or errors in the combination of component calibrations. In this phase also those calibrations must be performed which can only be done in the aircraft, such as control surface deflection measurements.

A second important step is the investigation of the interactions between the instrumentation system and the aircraft systems. The effect of noise in the flight test equipment produced by the aircraft systems can be detected by the method described in Section 8.4.2, but now all instrumentation input signals are kept constant and the aircraft systems are operated. Recordings can be made when the engines are running and when radio and other aircraft equipment are switched on. Influence of the flight test instrumentation equipment on aircraft systems can be detected by monitoring the standard aircraft instrumentation and communication/navigation equipment while operating the flight test instrumentation equipment, as, for example, switching cameras, recorders, telemetry transmitters, blowers, heaters, power supplies, and disconnecting and connecting the data acquisition electronics.

All these tests are necessary to build up confidence that the equipment will meet the design objectives under the expected circumstances. The absolute determination of accuracy in flight is unfortunately not possible. Only estimates can be made taking into account all possible sorts of errors. In some cases comparisons can be made with, for instance, photo panel indicators or cockpit indicators. At some point of time, the judgement must be rendered that the equipment is ready for use.

Once the equipment has been pronounced ready, it is guaranteed that somebody will initiate a request for a change to the measurements list. The danger here is that too little concern will be given to the effect this might have on the system performance. Small last minute changes are frequently made without proper checking for interactions and interference. The possibility exists that the qualification tests will be invalidated and this will perhaps not be noticed until the first flight. Actually, appropriate tests should follow each alteration.

8.4.4 Preflight and postflight checks

If the instrumentation equipment successfully passes the final total system check-out, the equipment enters its operational stage. From now on it will be in the hands of the engineers who operate and maintain it. An important part of their work is to prepare the equipment for each flight. An almost mandatory requirement is the use of a preflight checklist for all projects, whether big or small. An aborted flight caused by the fact that some small preflight item was overlooked can in no way be justified.

The preflight check should start with the following items: tie down of equipment, all connectors in place, mechanical condition of transducers, boxes, cameras, recorders, cabling, tubing and other equipment, check of BITE output, etc. Then the cameras and recorders must be reloaded. Each channel output should be checked for proper indication with all inputs in a known condition. This can either be done manually using the on-board displays or by making a test recording (possibly by means of telemetry) which can be analyzed in the data processing station. The preflight check should then be continued with a short functional test of the whole system. Finally, all switches and other controls must be put in the correct position.

A postflight check will be performed to ensure that the system is still functioning properly.

If the results of the flight test become available well before the next flight a postflight check may not be necessary.

After a flight, both the flight test engineer and the instrumentation engineer want to know, as soon as possible, the results of the flight test. For the instrumentation engineer no test can replace the output from the preprocessing phase as this will contain the ultimate evidence of proper functioning or failure.

8.5 REFERENCES

1. Telemetry standards, IRIG Document 106-71
2. C.E. Lowman — Magnetic recording, McGraw Hill, 1972
3. T.T. Walters — Concorde flight test instrumentation, Proceedings of the 6th International Aerospace Symposium, Cranfield, England, March 1970
4. J.L. Beilman — An integrated system of airborne and ground-based instrumentation for flying qualities research with the X-22 A airplane, Proceedings of the 7th International Aerospace Symposium, Cranfield, England, March 1972
5. Environmental conditions and test procedures for airborne electronic/electrical equipment and instruments, RTCA Document DO-138
6. Environmental test methods, MIL - STD - 810
7. Electronic equipment airborne, general specification, MIL - E - 5400
8. Environmental testing, aeronautical and associated equipment, general specification, MIL - E - 5272 C
9. Electric power, aircraft, characteristics and utilization, MIL - STD - 704
10. Guidance for aircraft electrical power utilization and transient protection, ARINC Report No. 413
11. General guidance for equipment and installation designers, ARINC Report No. 414
12. Mark 2 Aircraft Integrated Data System, ARINC Report No. 573
13. Electromagnetic interference, characteristics, requirements for equipment, subsystems and systems, MIL - STD - 461
14. Instrumentation grounding and noise minimization handbook, Air Force Rocket Propulsion Laboratory, Technical Report AFRPL-TR-65-1 (available through NTIS under number AD 612027)
15. R.L. van der Velde — The interface of AIDS with existing aircraft systems, National Aerospace Laboratory NLR, Amsterdam, The Netherlands, Report NLR TR 71120 U, 1970
16. E.L. Gruenberg (ed) — Handbook of telemetry and remote control, McGraw Hill, 1967

CHAPTER 9

ON-BOARD RECORDING

by

C. Roquefeuil

9.1 INTRODUCTION

On-board recording is the most generally used method of data storage in flight testing. Even when telemetry is used, the same data are often also recorded on board the aircraft to ensure that they will not be lost if the telemetry link should fail.

The earliest and simplest method of on-board recording was the use of a knee pad and pencil by the pilot or a human observer, who wrote down his readings of the instruments available in the cockpit. In the last few decades there has been a rapid development of first photographic methods and later tape-recording methods. This development has shown a double trend:

- a specialization between direct-indicating instruments (for the flight crew) and measuring devices specially mounted for flight test purposes
- a continuous increase in performance: number of recorded channels, bandwidth of each channel, accuracy, ease of processing, etc.

In the course of this development the following recording methods have come into general use for flight testing:

- photo-panel recorders (from about 1930)
- continuous-trace recorders (from about 1940)
- analog magnetic-tape recorders (from about 1950)
- digital magnetic-tape recorders (from about 1960).

Despite their different age, none of these methods are yet obsolete. Although the more modern methods are generally preferred for large-scale test programmes, the older methods can often be used very cost-effectively for tests where high performance is not a prime requirement, especially if there is no direct access to a complex data processing station. In this chapter the advantages and disadvantages of each of the methods will be discussed, in order to show the best fields of application for each method.

Other recording methods are used under special circumstances. Normal photo or cine cameras are used for making pictures of wool-tuft or ice-accretion patterns on wings, for measuring dynamic movements of the wing or the tail with respect to the central fuselage and for many other purposes. In some cases simple electro-mechanical counters are used to count the number of events (exceeding of a certain g-load, the occurence of errors in a digital instrumentation system, etc.); these counters are then read manually after each flight or even during flight. New recording methods, which are now still under development, may in the near future be used for flight testing also. These include electrostatic recording methods and the use of large-scale integrated semi-conductor memories. These will not be described here in detail, because they are not yet in general use for flight test purposes.

9.2 PHOTO-PANEL RECORDING

9.2.1 General aspects

In its simplest form, photo-panel recording makes use of a camera which makes pictures of the pilot's instrument panel at regular intervals. Generally, however, the lighting of the instrument panel is insufficient for this purpose and the application of extra lighting will be unpleasant for the pilot. Also, it is generally difficult to find a suitable place to mount the camera where it does not restrict the pilot's movements. Therefore, a separate instrument panel is generally used, which can be suitably lighted.

9.2.2 Advantages

- The basic structure of the recorder is simple and cheap. It can be constructed in any workshop.
- Installation and operation of the instrumentation system can be done by normal aircraft ground personnel without any special training.

- For most parameters the same types of instruments can be used as in the cockpit.
- The instruments can be easily interchanged to fit the requirements of the flight test programme.
- If the dials are engraved in engineering units, the readings can be directly used without applying calibrations if the accuracy requirements are not too high.
- Direct visual monitoring by a flight test engineer in the aircraft is possible if the recorder has been suitably designed. The flight test engineer sees exactly what the pilot sees.

9.2.3 Disadvantages

- In most cases the accuracy of the pointer instruments is rather low. There are, however, a few very accurate multi-pointer instruments, such as altimeters.
- The response characteristics of the pointer instruments limit the useful bandwidth to about 1 Hz.
- The most serious disadvantage for many applications is that the data processing must be done manually and is very time consuming. Automatic data processing is impossible.

9.2.4 Range of applications

As for most flight test programmes the disadvantages far outweigh the advantages, photo-panel recorders are only seldom used as the main recording system. Exceptions are, for instance, tests with sailplanes (where the availability of the instruments and simple installation are important) and for some types of training (where it is important that the students observe the same instruments as the pilots, either in flight or during replay on the ground).

In many flight test programmes photo-panel recorders are, however, still used for recording one or a few parameters for which recording with the more sophisticated main data system would be too costly. There are a few types of aircraft systems to which a normal instrumentation system cannot be directly connected. This may be because the signal deteriorates due to the extra load, or because the electrical signal is not meaningful as an additional mechanical correction is applied in the pointer instrument. In such cases the cheapest and quickest solution often is to mount the co-pilot's indicator in a photo-panel recorder and to accept the extra work involved in data processing. In ad-hoc tests of short duration such a solution is often the only feasible one, but even in large-scale prototype tests of civil and military aircraft a photo-panel recorder is often available for a few special measurements.

In the recent past, photo-panel recorders were often used as a back-up in case the more sophisticated instrumentation system failed. As the reliability of electronic systems has increased very much lately, this is hardly ever done now.

9.2.5 Typical installations

Transducers: All direct-indicating instruments can be used, such as pointer-and-dial instruments, digital indicators, etc.

Number of parameters: Usually below 10, though recorders with up to 100 parameters haven been used in the past.

Sampling rate: Up to 5 pictures per second. Higher rates can be used if pointer instrument response justifies it.

Recording duration: Up to several hours.

Size and weight: Size roughly a cube with face equal to the surface of the instrument panel, weight from 20 kg upward.

Synchronization: The camera can usually be actuated by an external time base.

9.3 CONTINUOUS-TRACE RECORDING

9.3.1 General aspects

In these recorders lines are produced which depict the variations of the input parameters with time. The continuous-trace recorders can be divided into two groups: pen recorders and photographic recorders.

In pen recorders the line is inscribed directly on a strip of paper or other material which moves past the pen at an approximately constant speed. Many types of pen recorders are available on the market, but for flight testing only a few types are used, and even those not very often. Some details of these recorders are given in Section 9.3.5.

In photographic recorders a light beam produces a line on photographic paper or film which moves past a slot at a constant speed. In the majority of these recorders normal photo-sensitive paper is used, which must be developed on the ground after the flight. Recently, recorders with an ultra-violet (UV) light source have come into use, in combination with special UV-sensitive paper. The lines on this paper become visible a few seconds after they have been inscribed. Details are given in Section 9.3.6.

9.3.2 Advantages of continuous-trace recording

- The results of the measurements are presented in a way which can often directly be used for interpretation.
- Parameters related to each other can be recorded so that their variations can be easily compared.
- With pen recorders and UV-recorders it is possible to present real-time information to observers on board the aircraft(for some applications even the delay involved in UV-recording can be too large for real-time application).
- In some photographic recorders recording elements can be used which combine the sensing device with a device for deflecting the mirror. This provides a simple and cheap instrumentation system.

9.3.3 Disadvantages of continuous-trace recording

- The number of channels that can be accommodated in a recorder is limited by the space available for mounting sensors and by the requirement that the traces must be distinguishable on the paper. Typically 5 to 20 channels are used, including time base and event markers.
- Accuracy is limited by the optical resolution (trace width divided by maximum deflection) and by paper shrinkage, as well as by errors of the sensors. Typical accuracy is 0.5 to 2 percent of full range.
- Linearity is often poor because of the "tangent effect" of the pen arm in pen recorders and the variable length of the optical path in photographic recorders.
- Bandwidth is not only limited by the dynamic characteristics of the sensors and their associated electric circuits and mechanical linkages, but also by the paper speed. A trace will only be well defined if the paper is moved more than four times the line width during one period of the highest frequency in the signal. Special problems occur, especially in photographic recorders, when the signal frequency varies much during one recording. The exposure at a certain point of the paper is proportional to the speed at which the spot passes it. In extreme cases the trace can be very thick and ill-defined when the input signal is constant, and so underexposed at high signal frequencies that it does not produce a visible trace. If only a certain part of the frequency range is of interest, the exposure can be optimized by adjusting the lamp voltage.
  The useful frequency range for most types of pen recorders is below 50 Hz. Photographic recorders can have frequency ranges up to several thousands of Hz.
- Although much effort has been put into the development of automatic processing equipment for continuous-trace recorders in the period before magnetic-tape recording had come into general use for flight testing, it must be said that in practice automatic data processing is not possible. There are, however, semi-automatic reading devices, which are very useful when continuous-trace recordings have to be converted into digital data (see Chapter 12).

9.3.4 Range of applications

For many types of flight tests, especially ad-hoc tests for trouble shooting, the continuous-trace recorder gives exactly the information that is wanted: a general indication of the variations of a few parameters with time and the possibility to determine reasonably accurate values at critical points. When pen recorders or UV-recorders are used, the traces are immediately available and can even be observed during flight. The recordings of normal photographic recorders must be processed after the flight, but this can be done in any darkroom. This can be a great advantage if tests are done from airfields without a data processing station. Because of this possibility continuous-trace recorders are sometimes used as quick-look devices for a few parameters in parallel with a larger and more complex tape-recording system.

9.3.5 Typical data, pen recorders

Few pen recorders have been specifically designed for the airborne environment. They are, nevertheless, used when direct visibility of the trace is a requirement. This will only be the case in relatively large aircraft, where test engineers can directly observe the traces. In such aircraft the environmental conditions usually are not extreme. It will, however, always be necessary to establish by tests whether the recorder can stand the environment to which it will be exposed, and to provide anti-shock mountings if required. The main advantage of pen recorders over photographic recorders, besides the possibility of reading the trace immediately, is their general availability. A disadvantage is, however, that the pen deflections are usually limited because adjacent pen mechanisms cannot overlap. Typical data on pen recorders are:

Sensors: mostly moving-coil type galvanometers with a moving arm carrying the stylus.

Writing system: scratching stylus (wax paper, aluminium foil), heated stylus with thermo-sensitive paper, low-voltage stylus with electro-chemically sensitive paper. Ink writing and high-voltage styli are unsuitable for airborne use.

Accuracy: 0.25 to 3%.

Max. bandwidth: generally less than 100 Hz. For a few types up to 1000 Hz.

Input: current from a source with specified internal resistance (for optimal damping).

Sensitivity: current sensitivity from 10 microamp/ cm,

Maximum deflection: 10 to 120 mm.

Paper width: 50 to 400 mm.

Number of channels: 1 to 20.

Paper speed: 0.05 mm/sec to 500 mm/sec. Most recorders can be used at several speeds (2 to 8), selected by an electrical switch or by changing gears.

Paper length: 5 to 100 m.

Recording duration: from a few seconds to several hours, depending on paper speed and length of paper

Size and weight: 2 to 20 dm^3, 3 to 30 kg, depending on the number of channels and the paper length.

NOTE: Special mention should be made of electrostatic recorders, which are now increasingly used in ground applications. In these recorders, the data are first quantified in N levels (typically N is 100). The electro-sensitive paper moves under a "comb" with N teeth. A (high) voltage supplied to the tooth which corresponds to the instantaneous value of the input signal produces a dark trace on the paper. If sampling is used, several parameters can be recorded simultaneously. As there are no moving parts, bandwidths of 3000 Hz and higher are possible. Although these recorders are not generally used in airborne applications as yet, it seems likely that this will occur in the near future. A problem still is the high voltage employed, which can cause sparks.

9.3.6 Typical data, photographic recorders

Many photographic recorders have been designed for airborne use and can withstand extreme environments. There are no internationally accepted standards for these types of recorders. Several groups of recorders exist now, where sensors are exchangeable between recorders of the same group but not outside the group. In UV-recorders of a certain group the same sensors can be used as in the normal recorders of that group.

The main features of the photographic recorders are:

Sensors: in some types of recorders only moving-coil galvanometers can be used, with different sensitivities, impedance and dynamic characteristics. In other types of recorders a large variety of sensors can be used. These can be divided into two groups: electrical sensors of many types such as moving-coil and moving-magnet galvanometers, ratiometers, frequency meters, on-off markers for the time base and for event marking, etc., and "direct" sensors in which pressures, accelerations and pendulum deflections directly move the mirror whose deflections are recorded, without the intermediary of electrical signals.

Writing system: a mirror in the sensor which deflects the light of a lamp. Focal length of the mirror (or the associated lens): 100 to 400 mm. Spot diameter: 0.2 to 0.4 mm.

Accuracy: generally 0.5 to 3% of full scale. With special multi-mirror coarse/fine transducers a much higher accuracy is possible. This system is especially used for pressure sensors.

Maximum bandwidth: For electrical sensors bandwidths of up to 10,000 Hz are possible, though for most types the bandwidth does not go beyond a few hundred Hz. For direct transducers the bandwidth is usually lower.

Input: For electrical sensors: current. For some types of sensors a specific source resistance is required for optimum damping.

Sensitivity: For electrical sensors: current sensitivity from 1 microamp/mm.

Maximum deflection: Generally up to 100 mm (limited by linearity error for a given focal length).

Paper or film width: 50 to 300 mm.

Number of channels: Generally less than 20. In a few types of recorders up to 50 channels are possible.

Paper speed: 0.5 mm/sec to 2.5 m/sec. Usually several speeds can be selected by means of a switch on a control box. Sometimes additional speeds are possible by changing gears.

Paper length: 5 to 200 m.

Recording duration: from a few seconds to many hours, depending on paper speed and paper length.

Size and weight: 2 to 20 dm^3, 1.5 to 20 kg, depending on the number of channels and the paper length. In a few cases the volume can be up to 90 dm^3 with weight up to 70 kg.

NOTE.

In a few cases the recorder, or the film cassette, are crash and fire proof. The recordings made by these recorders can generally be salvaged even when the aircraft has crashed.

9.4 ANALOG MAGNETIC TAPE RECORDING

9.4.1 General aspects

The essential elements of a tape recorder are the tape drive mechanism and the head assembly with the associated signal electronics. The tape drive mechanism must ensure that the tape moves past the head at constant speed, that the alignment of the tape with the head is very good and that the tape is pressed against the head with sufficient pressure. In general a number of tape speeds can be chosen by an electrical switch or by changing gears. The ratio between successive tape speeds, generally, is exactly 2 and they range for most types from 45 mm/sec (1 7/8 inch/sec) to 1525 mm/sec (60 inch/sec). The head assembly consists of a record head stack and (in most cases) a reproduce head stack. The record and reproduce amplifiers are often housed in the tape deck, often together with the required signal modulators and demodulators. If the electronics are housed outside the tape recorder, there is often a reproduce preamplifier in the recorder. If that is absent, the quality of the reproduce signal can be poor. The reproduce heads are then only used for signal monitoring and usually are called monitoring heads. Signal reproduction is then done on the ground in a special tape reproducer. Most flight test tape recorders are made to the IRIG specifications given in Reference 1. Descriptions of the different types of tape recorder used in flight testing are given in References 7 and 6.

The great majority of magnetic recordings is made on magnetic tape with a plastic backing. This backing is coated with a dispersion containing magnetic particles with relatively high coercivity. Only in exceptional cases (e.g. high temperatures) metal tape or wire are used. These are made of solid magnetic stainless steel. Normal magnetic tape is available in standard widths of ¼ inch (6.35 mm), ½ inch (12.7 mm) and 1 inch (25.4 mm). Many types of instrumentation tape are on the market, with different overall thickness, thickness of the magnetic coating, characteristics of the magnetic layer and backing material.

As the magnetic tape moves past the recording head, the magnetic state of the particles on the tape is changed by the magnetic field in the gap of the record head. When the magnetized tape passes the reproduce head, magnetic fluxes are induced in that head. These fluxes are, in first approximation, proportional to the currents which flowed in the record head. The voltages induced in the coil of the reproduce head are proportional to the time-derivative of the flux. The output voltage of the reproduce head is, therefore, zero when the magnetization on the tape is constant (i.e. the current in the record head has been constant). If the current in the record head was a sine wave with constant amplitude, then the output of the reproduce head will be a sine wave with an amplitude that increases proportional to frequency up to the point where the wavelength of the signal on

the tape becomes of the same order as the gap length of the reproduce head. The general shape of these amplitude characteristics is shown in Figure 9.1. It is also shown in that figure that a reasonably constant amplitude characteristic of the output voltage of the reproduce amplifier can be obtained if the amplification decreases with frequency (equalization). A more detailed discussion of the magnetic recording process is given in Reference 6.

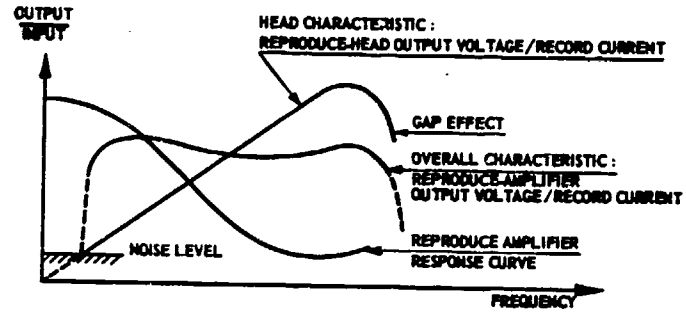


Figure 9.1 Record-reproduce characteristics for magnetic recording

In the direct recording method the input current to the record head is proportional to the input signal. It will be clear from Figure 9.1 that this method cannot be used for analog low-frequency signals and that even in the useful frequency range for direct recording the result will not be very accurate.
There is also another form of amplitude non-linearity, that is caused by the shape of the hysteresis curves of the magnetic coating of the tape. This can be corrected by mixing the data signal with a high-frequency bias signal. Direct recording is, therefore, only used for audio and high-frequency signals, where DC components are not of interest and where high accuracy is not required. It can be used to signal frequencies which are higher than those which can be recorded by a modulation method.

In analog modulation methods time intervals or frequency are used to convey the information, so that the poor amplitude characteristics do not affect the accuracy of the data transmission. Methods used in flight testing are pulse-duration modulation and frequency modulation, which will be briefly discussed below. Pulse code modulation or digital recording will be the subject of Section 9.5.

In pulse-duration modulation (PDM) the data are sampled and the individual values of the samples are recorded as pulse lengths on the tape. The principle of this modulation method is described in Chapter 10. A typical recording format, with calibration pulses for the zero and full-scale values, is shown in Figure 9.2. It has been used for flight testing in the past, but has now for the greater part been superseded by digital recording methods.

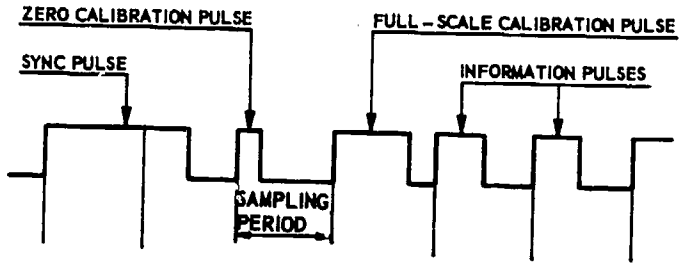


Figure 9.2 PDM signal format

In the large majority of analog flight test tape recordings frequency modulation (FM) is used. The principles of FM are described in Chapter 10. As in telemetry, frequency-division multiplexing and time-division multiplexing are also used. In the case of frequency-division multiplexing the multiplexed signals are not modulated on another carrier frequency as in telemetry, but are directly recorded on the tape.

In PDM and FM recording the tape speed has an important influence on the accuracy. Variations of the tape speed from its nominal value and fluctuations in the tape speed produce errors in the recorded information. Errors in the average speed, wow (low-frequency fluctuations) and flutter (high frequency fluctuations in the tape speed) can be reduced by servo control of the speed of the reproducer and/or by electronic means during reproduction. Both methods make use of a sine wave recorded simultaneously with the other parameters.

9.4.2 Advantages of analog tape recording

- Possibility of automatic data processing.
- Large number of data channels on one tape by use of time and frequency-division multiplexing.

- Large bandwidth.
- Analog form allowing easy display on instruments or continuous-trace recorders for quick look.
- Possibility to read the tape at a higher speed than the speed at which it was recorded.

9.4.3 Disadvantages of analog tape recording

- Limited accuracy, typically 0.5 to 2%.
- Need for digitizing on the ground if processing with digital computers is required.

9.4.4 Range of applications

Analog tape recording is the best method for recording high-frequency data (bandwidths in excess of several hundreds of Hz) and is unique for very-high-frequency data (bandwidths higher than 10,000 Hz up to several MHz). It can also be used with advantage when the output is directly used in analog computers and other analog processes, such as the reproduction of vibration patterns on electrodynamic vibrators. Another interesting application is simultaneous on-board recording of data transmitted to the ground by telemetry, for use in case the radio link failed. In applications where large quantities of data have to be recorded for automatic processing it is quickly being superseded by digital recording. A typical analog magnetic recording system is shown in Figure 9.3.

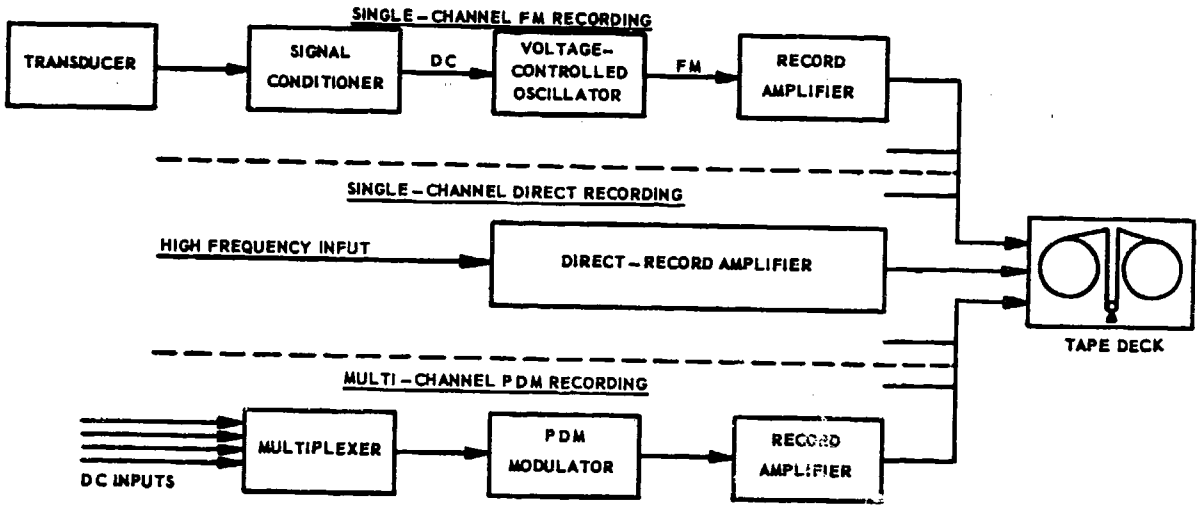


Figure 9.3 Typical configuration of an airborne analog magnetic recording system

9.4.5 Typical data on analog tape recording systems

Most flight test tape recording systems are designed according to the IRIG Telemetry Standards (Ref. 1). These give standards both for the tape recorder itself (head configurations, tape reels, requirements for test procedures for tape speeds) and for the associated electronics (record and reproduce amplifier characteristics, carrier frequencies for several FM systems, etc.). The following is mainly extracted from these standards.

Tape widths: ½ inch and 1 inch wide tapes are most generally used.

Head configurations: Usually 2 record head stacks and 2 reproduce head stacks. Number of tracks: 7 on ½ inch tape, 14 on 1 inch tape; in the near future 14 and 28, respectively.

Tape speeds: Increasing by factors of 2 from 15/16 inch/sec (23.8 mm/sec) to 120 inch/sec (3050 mm/sec). Typically 6 out of these speeds can be selected on one transport.

Record/reproduce bandwidths: For the purpose of standardization, IRIG has defined in Reference 1 four quality standards for tape recording systems:

Low band - direct record response to 100 kHz at 60 inch/sec.

Intermediate band - direct record response to 500 kHz at 120 inch/sec.

1.5 Wideband - direct record response to 1.5 MHz at 120 inch/sec.

2.0 Wideband - direct record response to 2 MHz at 120 inch/sec.

With these response characteristics the quality and characteristics of the tape transport mechanism, the heads and the associated electronics are defined. Systems of each quality

can also be used for FM and PCM recording. Most present-day recording systems are of the intermediate band type, but wideband systems are presently being used for on-board recording. Wideband recording has been used for many years for predetection recording of telemetry signals on the ground. Rapid progress is being made in this field and the standards may change again in the near future.

Direct recording: The pass bands for direct recording (± 3 dB) given in Reference 1 are shown in Table 9.1.

Table 9.1 Direct record bandwidths

Tape speed inch/sec	Pass band ± 3 dB (Hz)			
	Low band	Intermediate band	1.5 Wideband	2.0 Wideband
1 7/8	100 - 3,000	100 - 7,500	--	--
3 3/4	100 - 6,000	100 - 15,000	400 - 46,000	400 - 62,500
7 1/2	100 - 12,000	100 - 30,000	400 - 93,000	400 - 125,000
15	100 - 25,000	100 - 60,000	400 - 187,000	400 - 250,000
30	100 - 50,000	200 - 125,000	400 - 375,000	400 - 500,000
60	100 - 100,000	300 - 250,000	400 - 750,000	400 - 1,000,000
120	---	300 - 500,000	400 - 1,500,000	400 - 2,000,000

Single-carrier FM recording: In Table 9.2 the standard carrier frequencies and the signal frequencies are given for single-carrier FM recording for the low band, intermediate band and wideband group I systems. The frequency deviation for all these types is ± 40%. Wideband group II has different carrier frequencies and a ± 30% deviation; it is at present only used for predetection recording of telemetry signals on the ground.

Table 9.2 Single-carrier FM center frequencies and bandwidths

Tape speed (inch/sec)			Carrier center frequency (kHz)	Signal frequency range ± 1 dB (kHz)
Low band	Intermediate band	Wideband group I		
1 7/8	-	-	1.688	0 - 0.313
3 3/4	1 7/8	-	3.375	0 - 0.625
7 1/2	3 3/4	-	6.750	0 - 1.25
15	7 1/2	3 3/4	13.50	0 - 2.50
30	15	7 1/2	27.00	0 - 5.00
60	30	15	54.00	0 - 10.0
-	60	30	108.0	0 - 20.0
-	120	60	216.0	0 - 40.0
-	-	120	432.0	0 - 80.0

Frequency-multiplexed FM recording: IRIG gives no standards for this type of recording. In practice, telemetry modulation systems are used for tape recording. Both the proportional-bandwidth and the constant-bandwidth systems are used. They are described in Chapter 10. The subcarriers are, however, not modulated on an r.f. carrier but are added directly and recorded by the direct recording technique.

Dimensions, weight and tape length: A typical small flight test recorder measures 190 x 165 x 100 mm, weighs 3,2 kg and has a tape length of 200 m. A typical large flight test recorder measures 620 x 450 x 230 mm, weighs 36 kg and has a tape length of 3000 m.

9.5 DIGITAL MAGNETIC TAPE RECORDING

9.5.1 General aspects

For digital recording the input signals are sampled and digitized by the methods described in Chapter 5, and the digital "words" (each giving one instantaneous value of one parameter) are recorded sequentially on the tape. The digital codes are of the binary type, i.e. in the recording process only two magnetic states are used: saturation in one magnetic direction or the other. The method is, therefore, practically insensitive to the variations in amplitude response of the magnetic recording process. Because of the differentiating nature of the reproduce process, the information is actually contained in the rapid changes of state. The function of the detection process in digital recording is to determine whether at a certain moment there is a change of state or not. The reliability with which this can be done is one of the primary reasons for the increasing use of digital recording.

For a given tape recording system the important parameter determining the reliability is the bit packing density, usually expressed in bit/inch or bit/mm along a track. A high bit packing density will allow the recording of many data points on a given length of tape, but an extreme density will also increase the number of errors more than proportionally. It must be kept in mind that the errors occurring in digital recording are of a different nature than those in analog recording: in analog recording an error usually produces a small change from the correct value, but an error in one of the most significant bits of a digital word can produce a totally different value. If one bit is missed, a large part of a recording can become unintelligeable if no proper measures have been taken. The main factors determining the achievable bit packing density are:

- the quality of the tape transport used
- whether parallel or serial recording is used
- the code and the redundancy methods used
- the tape quality.

These aspects will be discussed separately below. But before that is done, a few words must be said as to what error rates can be accepted. Of course, it is quite unacceptable that one error should make it impossible to read a complete tape. The tape format can be chosen so that this can be made practically impossible. An error in one bit will, then, make one word or at most one frame unintelligeable. As the errors are usually big and only occur occasionally and independently, the errors can in most cases be detected by a computer programme comparing the consecutive values of each parameter. The aberrant or unintelligeable values can then be eliminated by the computer. The acceptable probability of an error will depend on the type of measurement made, but need in most cases not be extremely low. In most cases probabilities of 1 in 10^5 or even 1 in 10^4 words will be acceptable.

The quality of the tape transport systems is very important for digital recording systems. The values of the average tape speed in the record and reproduce systems are not as important as in FM systems, because they do not directly affect the signal values. If the tape speed differs too much from its nominal value, the reading errors will increase or it may even be impossible to read the tape. Fluctuation in the tape speed (wow and flutter, see Section 9.4.1) can cause uncertainty whether a change of flux belongs to a certain bit or to the previous or next bit. The effect of these speed fluctuations can be reduced by the use of "self clocking" codes.
A very important aspect is skew, which causes flux variations recorded simultaneously on different tracks to pass the gaps of the reproduce heads with (small) time differences. Static skew is caused by misalignment of the head stacks in the record and/or reproduce deck or by misalignment of the gaps in a head stack. For fixed combinations of record and reproduce decks a correction for static skew can be installed in the reproduce systems ("deskewing"). Dynamic skew is caused by angular fluctuations of the tape.

Skew has an important effect on the achievable bit packing density if parallel recording is used, i.e. if the bits of each word are simultaneously recorded on different tracks of the tape. Bit densities between 200 and 600 bits/inch (8 to 24 bits/mm) are generally used in airborne recorders. In serial recording all bits are recorded sequentially on one track. If suitable codes are used, bit packing densities of 1200 - 3000 bits/inch (48 - 120 bits/mm) and even higher are used for airborne recorders. A disadvantage of serial recording is that only one track is used at a time. In practice this often is not serious because:

- some recorders are designed so that at the end of a track the tape direction is reversed and recording is continued on another track ("shuttle" or "reciprocating").
- the other tracks can be used for recording other information. If analog and digital information have to be recorded simultaneously, the other tracks can be used for the analog information. If very much digital information must be recorded, a separate commutator-digitizer system can be used for each track.

The most generally used binary codes are shown in Figure 9.4. The NRZ codes have the disadvantage that, if a large number of consecutive "zeros" occur, their exact number will be uncertain if tape speed variations have occurred during that time. In the biphase codes there is one flux reversal for a "zero" and two flux reversals for a "one". Here the speed variations can be detected immediately, they are therefore called "self-clocking" codes. Although the number of flux reversals per bit of the biphase codes is twice that of the NRZ codes, higher bit densities can be achieved with them. They are nearly always used for high-density serial recording.

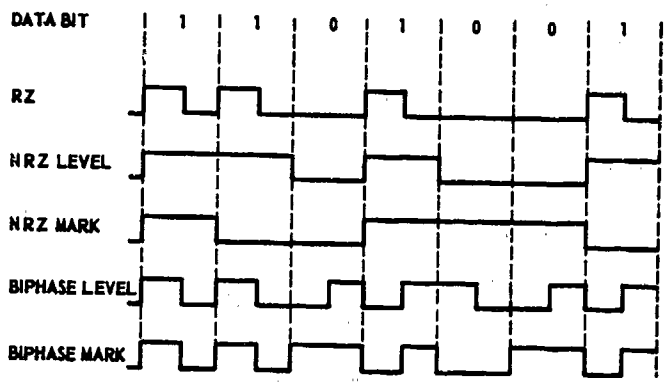


Figure 9.4 Digital modulation methods

In order to simplify the reading process and to detect or even correct errors, more information than only the measured values is recorded on the tape. The tape format usually includes the following items:

- A tape identification, including the flight number, date, test number, time and any other information which may be required for making easier the processing of the tape. In some flight test systems all calibrations are recorded on the tape before or after the flight, sometimes with an identification of the types of manoeuvres recorded, so that the data processing of each tape is almost self-contained.
- Special synchronization characters which mark the beginning of a new frame of a commutation cycle (frame sync) or a new word (word sync). These consist of unique patterns of bits which can be detected as such by the computer. If the recording becomes unintelligeable because the bit synchronization has been lost, the computer can restore this synchronization at the next synchronization character.
- Redundant bits which can be used to detect errors. The simplest form is the parity bit: for each word one additional bit is recorded, which indicates whether the number of "zeros" in the word is odd or even. The parity bit allows the detection of single errors in a word. More redundant bits can be added to each word, even to the extent that a certain number of errors can be corrected by the computer (error-correcting codes). Other kinds of redundancy are also used. One form is recording identical serial information on two tracks of the tape, so that most errors can be detected by comparing the two tracks.

The quality of the tape can have an effect on the number of errors. On instrumentation tapes the number of "dropouts" (places where unregularities in the magnetic layer occur where recorded information can be lost) is very small. It will increase if the tape has been used several times. In many flight test centres flight tapes are only used once (sometimes after an initial run on a ground recorder).

Flight tapes can be read on standard digital computer tape decks on the ground only if they meet a large number of requirements: they must be ½ inch wide, the bit density must have certain values, there must be inter-record gaps, etc. In general, computer-compatible tapes are not made in the aircraft. The reasons for this are discussed in Chapter 8. Normally flight tapes are replayed on the ground and transferred in the computer-compatible format to another tape. This latter tape can then be the input to the computer.

9.5.2 Advantages of digital tape recording

- High accuracy. If a sufficient number of bits are used, the accuracy only depends on the accuracy of the signal presented to the digitizer.
- Easy input of all kinds of data, especially of data which is already in digital form (for instance from digital systems already available in the aircraft).
- Possibility to record a large number of channels. In existing systems up to 2 thousand parameters are recorded.
- Easy automatic data processing on the ground, especially by digital computers.

9.5.3 Disadvantages of digital tape recording

- Limited bandwidth of the individual channels. The sampling rates of the individual parameters are seldom above 150/sec. Some improvement can be obtained for individual channels by supercommutation (see Chapter 10).
- Information density on the tape is usually lower than in analog magnetic recording.
- Due to the sampling required, aliasing errors can occur if the sampling rate is not adapted to the maximum signal frequency. Time correlation by interpolation will be necessary if channels have to be compared at exactly the same times.
- Quick look after the flight requires more complex equipment than the other recording methods.

9.5.4 Range of applications

Digital magnetic recording is the best choice for the storage of a large quantity of relatively low-frequency data, intended for extensive automatic data processing on the ground. Typically average signal frequency ranges up to 50 Hz can be handled (with higher frequency ranges for individual channels by supercommutation); there is a trend to use digital recording for higher frequencies. A typical digital recording system is shown in Figure 9.5.

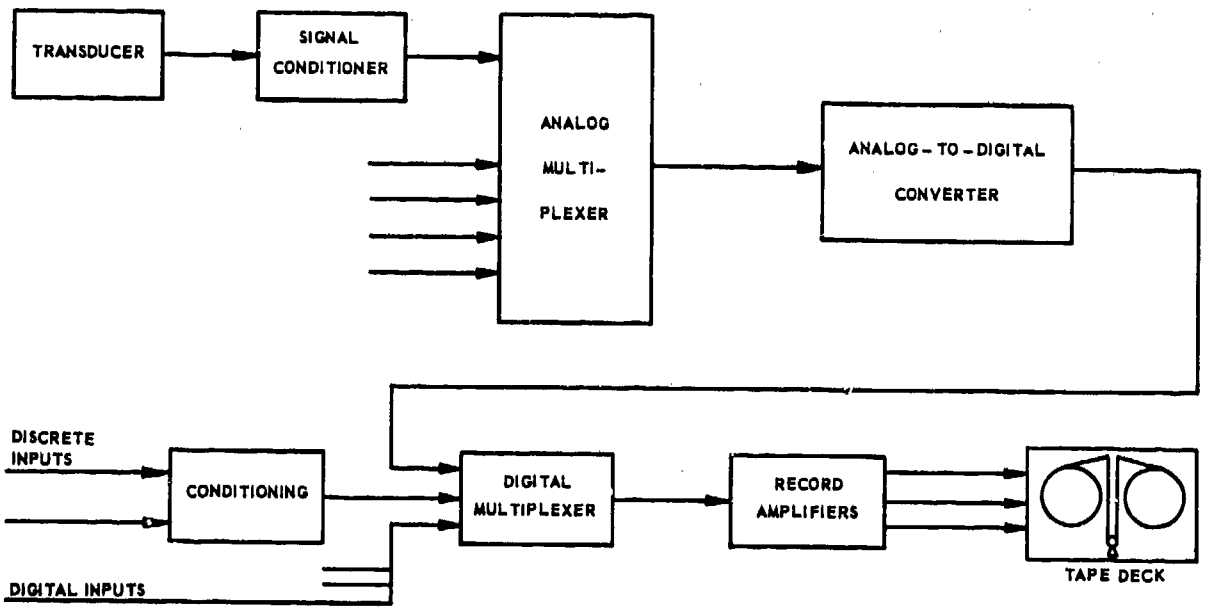


Figure 9.5 Typical configuration of a digital magnetic recording system

9.5.5 Typical data on digital tape recording systems

The IRIG standards only give complete standards for NRZ-Mark type recording (both parallel and serial) at packing densities of up to 1000 bits/inch (40 bits/mm). In an appendix serial biphase recording with packing densities of up to 20,000 bits/inch is briefly mentioned, but no detailed standards are given. Though this method is increasingly used for airborne recording, it is still so rapidly developing that standardization is not yet opportune.

Tape width: ½ inch or 1 inch. For computer-compatible recording ½ inch tape is required.

Number of tracks: IRIG standards specify 16 or 31 tracks for PCM recording. For high-density biphase recording analog-type recorders are often used with 7 or 14 tracks. For computer-compatible recording 7 or 9 tracks on ½ inch tape are required.

Bit packing densities: The IRIG standards mention packing densities of up to 1000 bits/inch for NRZ recording. Biphase recording is used at 6000 bits/inch or even higher. For computer-compatible tapes the requirements are 200 of 556 bits/inch track on 7 tracks or 800 bits/inch track on 9 tracks.

9.6 CONCLUSION

Unless telemetry is used as the main data transmission channel, airborne magnetic tape recording is the most generally used method for data storage in flight testing. Even in large sophisticated systems, continuous-trace recorders are used for quick instrumenting for ad-hoc problems, for tests where immediate visibility of the data is essential and for quick-look purposes. For small ad-hoc tests in operational aircraft, continuous-trace recorders are still extensively used. Photo-panel recorders are still used occasionally in cases where it is difficult to obtain any other meaningful output from an instrument than that of the indicator delivered with it.

Digital recording is the most generally used method for recording large quantities of data with relatively low bandwidths. It is still advancing in areas where other recording methods were more popular recently. Nevertheless, analog magnetic recording is still extensively used for recording high-frequency data. The existing IRIG standards, to which most of the equipment on the market is designed, call for different recorders for digital and analog recording. The development of high-density serial recording techniques makes it possible to record both on the same recorder. At the present time this still requires the use of custom-made electronic equipment.

The production of computer-compatible tapes in airborne recorders is not general practice (see Chapter 8). It is generally preferable to have special equipment in the ground station for converting the flight tapes into computer-compatible tapes (see also Chapter 12).

9.7 REFERENCES

1. - Telemetry standards, IRIG Document 106-71
2. G. Petit — Systèmes d'enregistrement, Centre d'Essais en Vol, Brétigny (1967)
3. P. Perreau — L'enregistrement magnétique de mesures, Editions Eyrolles, Paris (1969)
4. H.G. Zerkle — Flight recording in NATO countries, AGARD AR-39 (1972)
5. M. Hecht, A. Guida — "Delay modulation", Proc. IEEE, July 1969, pp 1314-1316
6. G.E. Bennett — Magnetic recording of flight test data, AGARDograph Nr. 160, Vol. 6 (1974)

CHAPTER 10

TELEMETRY

by

A. Becker

10.1 INTRODUCTION

A measuring system with telemetry in general consists of transducers, signal conditioning circuits, an airborne multiplexer and a radio frequency transmitter in the aircraft, and on the ground an rf receiver, a demultiplexer and a data storage system (usually a tape recorder); in most cases a data (pre)processing system with displays is added for on-line data analysis. The telemetry part of the system will be discussed in this chapter.

It consists of the multiplexer with the associated data modulators, the rf link, the demultiplexer, the data demodulators and the ground recording equipment. The methods of on-line data processing will also be briefly considered. In connection with on-line data processing, telemetry has become a powerful means of increasing the capability and efficiency of flight testing.

Telemetry of flight test data has a number of advantages over the use of on-board recording: a telemetry system has less weight and volume, it is less sensitive to extreme environmental conditions than the on-board recorder and it has better quick-look and on-line data processing capabilities. In some types of flight test it would be almost impossible to collect a sufficient quantity of data without telemetry. The use of a second telemetry link from the ground-station to the aircraft (tele-command link) can provide further improvement of the flight test efficiency.

On the other hand there are a few drawbacks: the range is limited by the physical characteristics of wave propagation, and there are problems with the mounting of on-board antennas and with dropouts of data reception due to fading in the radio frequency channel by multiple propagation. Detailed comparisons are given in Ref. 7 and 8; see also Chapter 8. The telemetry chain is shown in Figure 10.1.

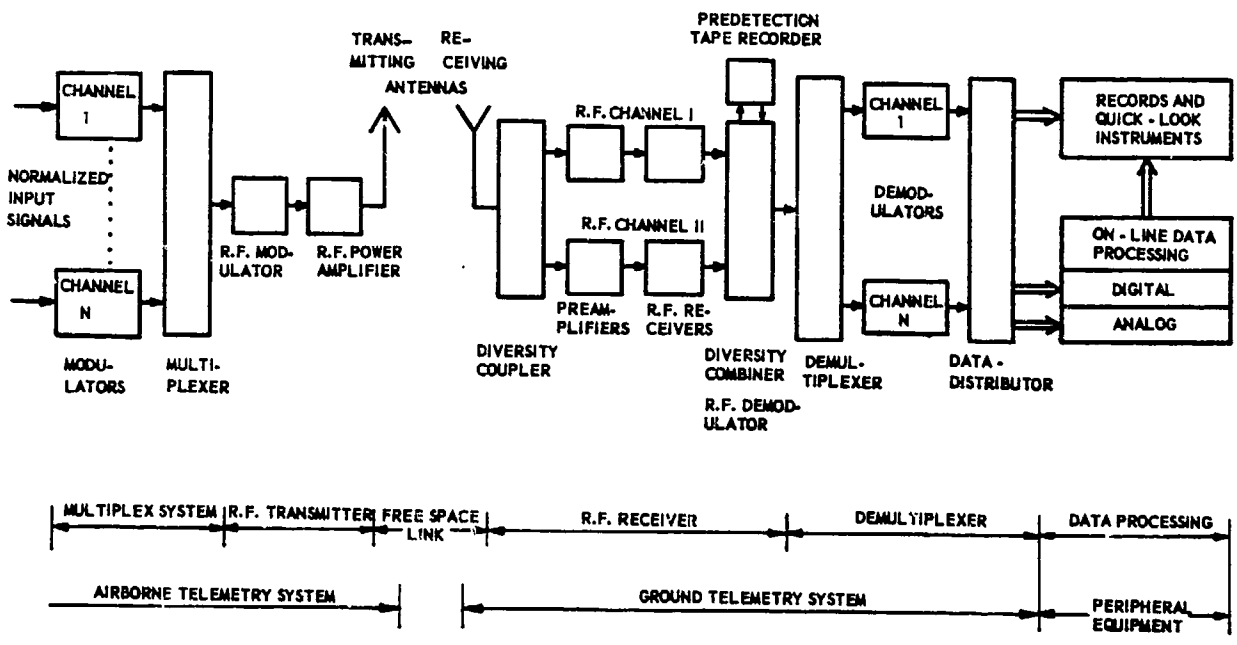


Figure 10.1 Block diagram of a telemetry system

The airborne system consists of the multiplexer, the rf transmitter and the on-board antenna. The radiated electromagnetic wave induces an rf voltage in the receiving antenna. This voltage is amplified and filtered by the receiver in order to eliminate unwanted signals and noise. The demultiplexer decomposes the receiver output signal and recovers the original data. Finally the data processing equipment converts the received data into the proper form for the user.

10.2 MODULATION AND MULTIPLEXING

10.2.1 Description of the basic methods

In general, the purpose of modulation is to match a signal to a specific transmission channel. The purpose of multiplexing is to transmit two or more signals over the same data channel without crosstalk. In practice the signal is often subjected to both processes. Therefore, modulation and multiplexing are treated in the same chapter. The general definitions are explained in more detail by Figures 10.2 to 10.5.

Four different objectives of modulation are illustrated by Figure 10.2. These are

a) shifting the signal spectrum to the frequency band of the transmission channel; e.g. shifting the voice spectrum by amplitude modulation to the assigned radio-frequency voice communication channel,

b) widening the shifted signal spectrum in order to get better protection against channel noise; e.g. by using frequency modulation[x)],

c) grouping a set of signals by means of modulated subcarriers or pulses and modulating the rf-carrier by this composite signal (frequency-division multiplexing or time-division multiplexing, respectively),

d) matching a signal to a specific channel, e.g. to a tape recorder direct channel (overcoming the lack of DC-response and the inconstancy in amplitude transmission of this channel, see Section 9.4).

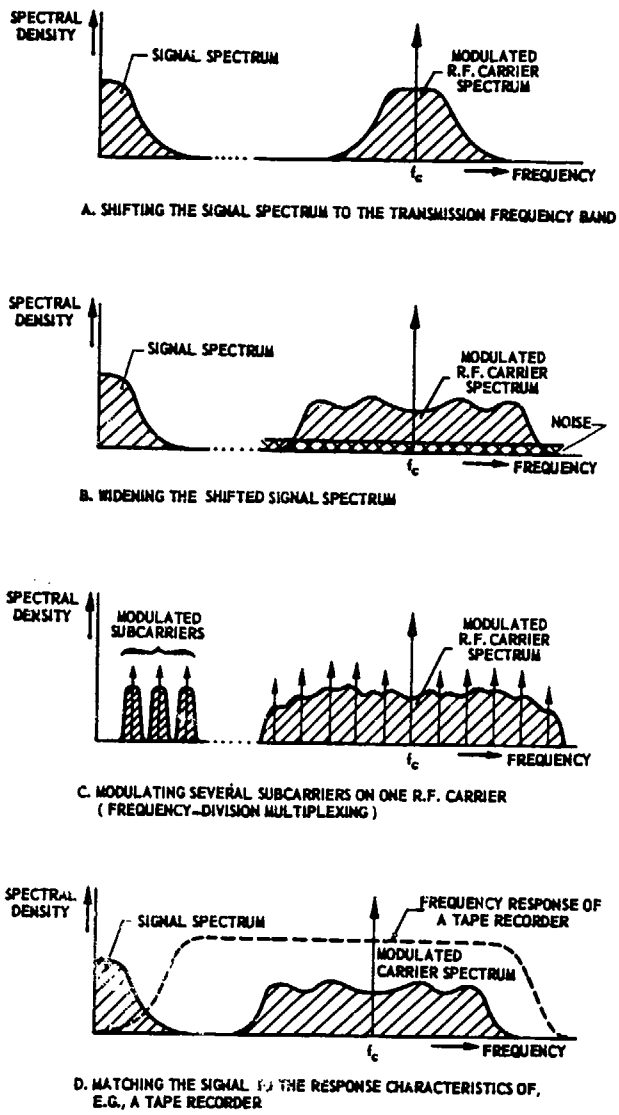


Figure 10.2 Objectives of modulation

---

x) Some modulation methods make use of the well-known trade-off between signal-to-noise ratio and bandwidth. They obtain better signal-to-noise ratios at the output of the demodulator by manipulating bandwidth and shape of the spectrum. As a rule it will be advantageous to use a modulation method which occupies all the available channel bandwidth.

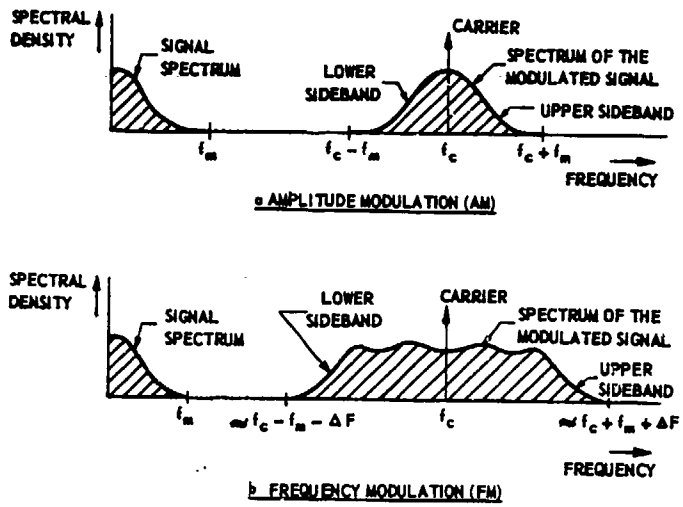


Figure 10.3 Continuous modulation methods

The usual modulation methods are shown in Figures 10.3 and 10.4. We have to distinguish between the continuous modulation methods and the pulse modulation methods. In the first case the parameters of a sinusoidal carrier (amplitude, frequency and phase) are controlled by the signal voltage. The modulated carrier can be described best in the frequency domain by its spectrum (see Fig. 10.3). For the pulse modulation methods, the parameters of a pulse carrier (amplitude, duration) are controlled by the signal voltage (see Fig. 10.4). In this case the modulated carrier can be displayed more clearly in the time domain by its time function.

The time function of the modulated carrier for amplitude modulation (AM) is:

$$u(t)_{AM} = U_c \cdot \left\{ 1 + m.s(t) \right\} \cdot \cos(\omega_c \cdot t) \qquad (10.1)$$

with the carrier wave $U_c \cdot \cos(\omega_c . t)$. The normalized signal time function $s(t)$ is bounded by ± 1. The range of the modulation factor m usually is $m \leq 1$. The spectrum of the modulated wave consists of one line at the carrier frequency ω_c and an upper and lower sideband. The upper sideband is obtained by shifting the signal spectrum by ω_c along the ω-axis. The lower sideband is the image of the upper sideband, symmetrical to ω_c. Therefore, the bandwidth of the AM spectrum is twice the bandwidth of the original signal spectrum (see Ref. 1, 2, 4 and 5).

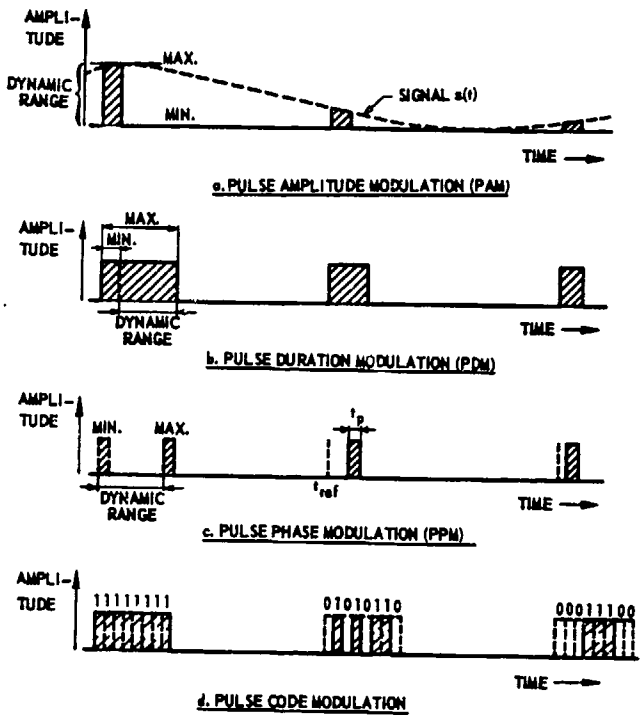


Figure 10.4 Pulse modulation methods

The main drawback of AM is that most of the power of the modulated wave is required for the carrier. In the demodulator the carrier is used only for switching the AM wave in order to recover the demodulated signal. It contains no signal information. Since it is possible to obtain the switching signal for the demodulation process in other ways, - e.g. by manipulating the sidebands -, it is more efficient to suppress the carrier before transmission (double-sideband suppressed-carrier modulation (DSB)). However, the hardware of DSB is more complex than that of the simple AM. In the case of AM and DSB all the signal information is contained in each of the two sidebands. Therefore, one sideband may be suppressed by filters and the single-sideband suppressed-carrier modulation (SSB) is obtained. The bandwidth of SSB is equal to that of the signal, and half the bandwidth of AM and DSB. The signal-to-noise ratio is equal to that of DSB but, because of the smaller bandwidth, one can handle twice as many data channels in a given frequency range as with AM and DSB. The main drawbacks of SSB are the high degree of hardware complexity and the lack of DC response. The spectra of DSB and SSB may easily be derived from the AM spectrum displayed in Figure 10.3.

For a deeper understanding of modulation it may be worth mentioning that a close connection exists with the sampling theorem, which is discussed in Chapter 6. We assume a signal spectrum with an upper frequency limit f_m. When then the carrier frequency f_c is less than 2 f_m, there will be frequencies at which the unmodulated and the modulated signals overlap. This will cause aliasing errors (or errors of commission as they are called in Chapter 6) when the signal is demodulated. The AM process may be regarded as the sampling of a signal s(t) by the sine wave.

Frequency modulation (FM) (Figure 10.3b) is a wideband modulation method which makes use of an extended bandwidth in order to improve the signal-to-noise ratio. Because of the relatively simple hardware FM is of great importance for flight testing. In FM the frequency of the carrier wave is modulated in the following way

$$f_{FM} = f_c + \Delta F . s(t) \tag{10.2}$$

where f_c is the frequency of the modulated carrier, ΔF is the frequency deviation and s(t) is the normalized signal (see above). It can be shown (see Ref. 1, 2, 3, 4 and 5) that the increase of the signal-to-noise ratio is proportional to the ratio

$$M = \frac{\Delta F}{f_m} \tag{10.3}$$

M is the so called modulation index and f_m the highest frequency component of the signal spectrum (see Fig. 10.3b). Unfortunately, the bandwidth of the FM-spectrum also increases as a linear function of ΔF, thus limiting the obtainable gain because of the general restrictions on available bandwidth. For FM subcarriers modulation indices of 5 are used in practice for flight testing.

A special case of FM is the phase modulation (PM). This is accomplished by letting the signal s(t) control the carrier phase instead of the carrier frequency. Its special feature is a preemphasis which increases the amplitude of the signal spectrum linearly with frequency.

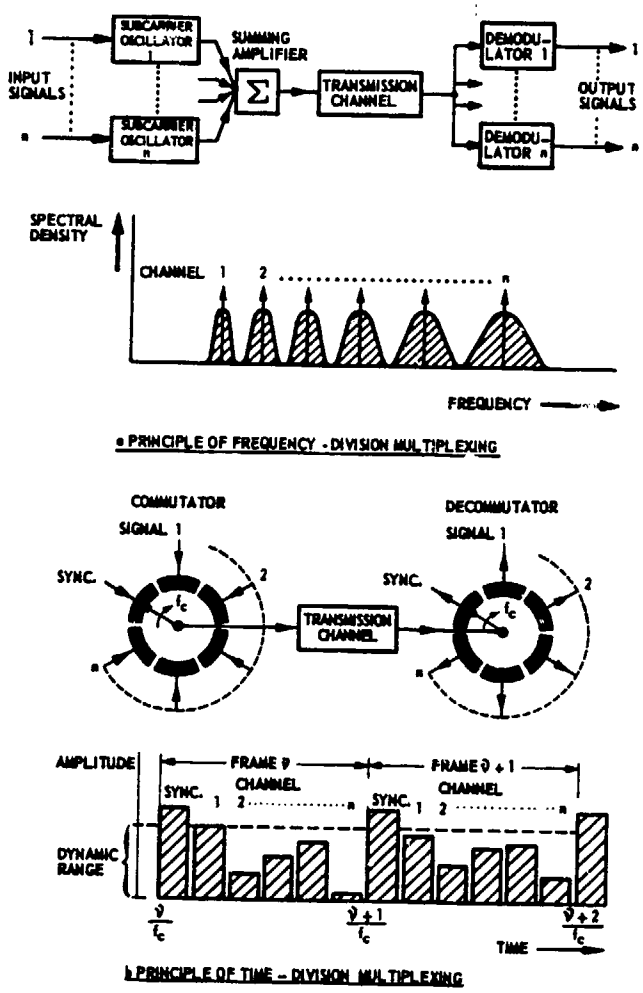


Figure 10.5 Methods of multiplexing

In pulse amplitude modulation (PAM) (Fig. 10.4a) the signal s(t) is sampled at discrete points in time. This process is described in detail in Chapter 6. All considerations of that chapter apply directly to PAM.

Pulse duration modulation (PDM) (Fig. 10.4b) is obtained by converting the amplitude of the PAM samples into a pulse duration. Thus a train of pulses with variable width is generated, and the dynamic range of the signal is transformed from the amplitude domain to the time domain. The minimum value of the signal s(t) corresponds to the shortest pulse duration; the maximum value corresponds to the longest pulse duration. The amplitude of the PDM pulse train remains constant. PDM, as FM, is a wideband modulation method. It is only used for simple systems (Section 10.5).

For the sake of completeness, pulse position modulation, or pulse phase modulation (PPM), is also displayed in Fig. 10.4c, though it is not a standard modulation method in telemetry. In this case the relative position of a pulse is controlled by the signal. A time reference is required for demodulation.

Due to the great technological progress in integrated circuits, the use of pulse code modulation (PCM) has become important during the last few years. In this method the PAM samples are

coded in a "word" of N pulses, using only the levels 0 and 1. Being a digital method, any required accuracy can be obtained by proper choice of the word length N. Besides, PCM makes excellent use of the law of exchangeability between signal-to-noise ratio and bandwidth. PCM is widely used in time domain multiplexing systems. Serial format PCM can be derived from a PAM signal by an analog-to-digital converter with a serial output. The clock frequency for the A/D converter must be N-times the PAM sampling frequency. This obviously shows the increase in bandwidth. N, the number of bits for each sample, is determined by the required amplitude resolution. On the other hand it is clear, that PCM is less sensitive to errors due to noise, because only two levels of the signal are possible. There are various formats for encoding the two levels 0 and 1. In Fig. 10.4d the "non return to zero-change (NRZ-C)" format has been used. For further details see Sections 5.3.5 and 9.5 and Ref. 6.

Figure 10.5 illustrates the two multiplexing methods used in practice: frequency-division multiplexing and time-division multiplexing.

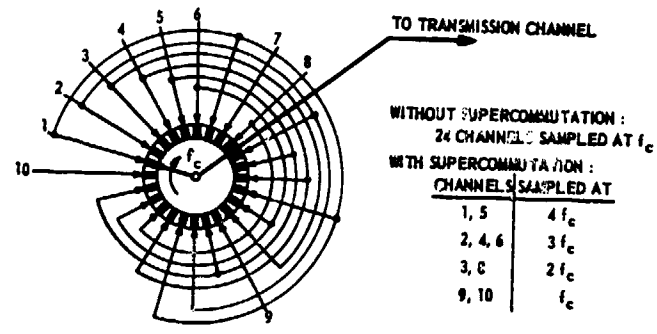
The method of <u>frequency-division multiplexing</u> (Fig. 10.5a) is generally used with continuous modulation methods, such as AM, DSB, SSB or FM. Each data signal modulates a subcarrier with a different frequency. By proper selection of the subcarrier frequencies, overlapping of the modulation spectra can be avoided. At a receiver end of the transmission link the individual subcarriers are separated by bandpass filters. The data signals are recovered by demodulation of the subcarriers.

On the other hand, <u>time-division multiplexing</u> is generally used with pulse modulation methods, such as PAM, PDM, PPM and PCM. Figure 10.5b is based on PAM. A commutator, e.g. a rotary switch, samples n different data signals with the same sampling frequency f_c, but at consecutive points in time. Thus, a train of non-overlapping pulses is generated which may be decommutated by a synchronously running switch at the receiver end of the transmission channel. In order to obtain the required synchronism, a synchronisation signal must be inserted in the pulse train, which can be detected by the decommutator and can be used for synchronising the position of the switch. Therefore, the synchronisation signal usually is given a value outside the dynamic range of data signals.

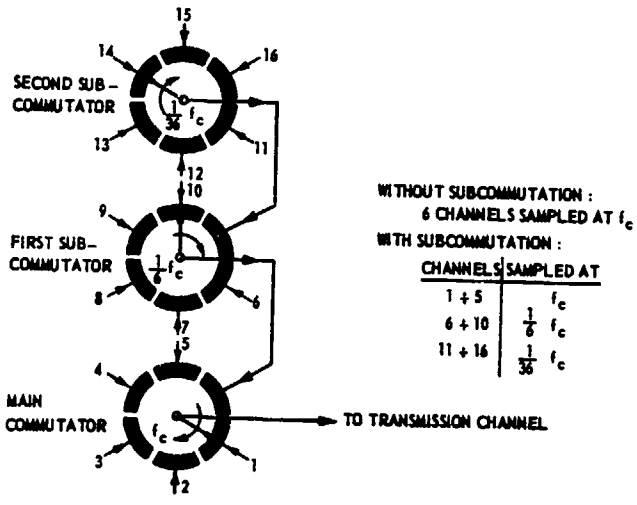
Besides making possible the efficient use of the available transmission channel bandwidth, time-division multiplexing allows a simple exchange between data channel bandwidth and the number of channels by supercommutation and subcommutation techniques. Both methods are shown in Fig. 10.6.

<u>Supercommutation</u> increases the sampling frequency of a channel by sampling the data signal more than once per frame. This can be done by paralleling some channels of the commutator. Obviously, the number of channels decreases. The example in Fig. 10.6a shows the substitution of 24 channels with a sampling frequency of f_c by 10 channels with different sampling frequencies ranging from f_c to $4.f_c$.

<u>Subcommutation</u> means the decrease of the channel sampling frequency by substituting one channel of the main frame sampling frequency f_c by n channels of a subframe using a sampling frequency f_c/n. The example in Fig. 10.6b shows the increase



a. SUPERCOMMUTATION



b. SUBCOMMUTATION

Fig. 10.6 Examples of supercommutation and subcommutation principles

of the number of channels from 6 channels using a sampling frequency f_c to 16 channels using sampling frequencies ranging from f_c down to $f_c/36$ by means of two subcommutation processes in cascade. It should be mentioned that mechanically rotating switches as drawn in Figures 10.5 and 10.6 are hardly used any more in flight test systems. Subcommutation can, however, be used in a similar way in commutators using relays or electronic switches (see Section 5.3.4).

10.2.2 Modulation and multiplexing used in telemetry systems

In telemetry systems at least two modulation processes are used in cascade. The first is required for each of the multiplexed signals and the second for matching the output signal of the multiplexer to the assigned radio frequency channel. The latter modulation method generally is FM with only a few exceptions. Telemetry systems are standardized by the Inter Range Instrumentation Group (IRIG), see Reference 6.

The FM/FM telemetry system uses frequency division multiplexing. The data signals modulate subcarriers with FM (standardized frequency deviation ± 7,5% or 15% with optional wideband channels). The maximum number of channels is 21 (for the P-band rf channels limited to 19). The subcarrier frequencies are located between 400 Hz and 165 kHz. This is true for the proportional bandwidth system, in which the bandwidths of the subcarrier channels increase proportionally to the subcarrier frequency. The constant bandwidth system also provides 21 data channels (15 channels for the P-band frequencies). The subcarrier frequencies are located here between 16 kHz and 176 kHz. The data bandwidth of all channels is equal. Consequently, the signal delay in all channels is equal and the time correlation between the channels is preserved (see also Chapter 3). The available hardware is proven and reliable. This is especially true for airborne subcarrier oscillators and for ground subcarrier discriminators. Two further systems using frequency multiplexing have been developed: the DSB/FM system and the SSB/FM system. Both systems make better use of the available transmitter power than the standardized FM/FM system. Because of the lack of DC response of the data channel, however, SSB/FM is not suited for general applications. DSB/FM has excellent properties, especially for high frequency data. But, because of historical reasons and the perfect technology of the FM/FM technique, DSB/FM is not in widespread use.

Besides using the rf channel efficiently, the PAM/FM system has some further advantages which may recommend its use. Being a time multiplex system it can accommodate a large number of data channels with highly different bandwidths by using supercommutation and subcommutation techniques. The technology of PAM multiplexers has made great progress in the last few years. At present a 16 channel multiplexer on one chip is already available and further progress in medium scale integration of PAM circuitry can be expected.

In modern flight testing, PCM/FM systems are more and more used. PCM provides the same flexibility as PAM, with the possibility of attaining higher accuracies. Very accurate analog-to-digital converters are available in integrated circuitry. Thus, the drawbacks of complexity and price will be reduced. Hitherto special decommutators were used in most ground stations. Because computers are more and more used, decommutation is often done by a computer along with certain on-line data processing. The bit synchronizer, however, which has to detect the bit sequence in the noisy background, should preferably not be integrated into the computer.

All three telemetry systems mentioned above make use of FM in the rf channel. This is the only method standardized by IRIG. The other continuous modulation methods as AM, DSB, SSB, which may also be used for rf modulation, are of little importance.

Mixed systems are often used in practice, because only few flight test signals have a wide bandwidth, while the majority has a narrow bandwidth. Because of past technological difficulties in producing commutators and decommutators with sufficiently high sampling rates, these high frequency data signals were transmitted by frequency multiplexed channels. On the other hand economical reasons and the moderate number of available frequency-multiplexed channels require the use of time multiplexing for the low frequency data by, for instance, the PAM/FM/FM system. Due to the recent progress in high speed integrated circuits, wideband PAM and PCM channels are currently available. Therefore, straightforward time multiplexing is preferable because of the high flexibility (supercommutation and subcommutation) together with the efficient use of the available bandwidth.

Finally, the inaccuracies introduced by the processes of modulation and multiplexing must be considered. Errors, originating from hardware imperfections (e.g. zero and gain drift of amplifiers, non-

linear distortion) should be distinguished from errors originating from peculiarities of the methods used in the system (e.g. sensitivity to noise in the transmission channel). The first class of errors is subject to the technological progress, whereas the latter class must be regarded as inherent to the system.

As mentioned above, wideband modulation methods incorporate a gain in signal-to-noise ratio in so far as transmission channel noise is concerned. Because of the twofold modulation in telemetry, the system performance is characterised by the overall bandwidth requirement and the signal-to-noise ratio at the output of the demultiplexer. Therefore, the question for the optimal system is: which combination of two modulation processes assures the maximum data bandwidth (maximum information rate) and meets a given rf bandwidth limitation as well as a required accuracy. It has been found (see Ref. 9) that PAM/FM is the optimum system in the case of low to medium accuracy requirements (1 to 3 %), while PCM/FM is best with high accuracy requirements (accuracy better than ± 0,5 %).

On the other hand the hardware of the FM/FM system is very refined because of the long period of usage and the high level of knowhow in production. Therefore, the first-mentioned group of errors is relatively low in FM/FM. As PAM technology progresses, PAM/FM will be used increasingly in the near future.

10.3 THE RADIO FREQUENCY LINK

The rf link is the connection between the airborne terminal and the ground station. Because of the following reasons, relatively high transmission frequencies must be used:

(a) The electrical length of an antenna must be a significant fraction of the wavelength for reasonable radiation efficiency. The small size required in airborne applications indicates wavelengths smaller than 3 m (frequencies greater than 100 MHz).

(b) The high bandwidth required for data transmission is only available at high frequencies. According to IRIG standards (see Ref. 6) three frequency bands are available for telemetry: In the range of 216 - 260 MHz (P band) are 62 channels with 500 kHz bandwidth each, in the range of 1435 - 1540 MHz (L band) are 100 channels with 1 MHz bandwidth each and in the range of 2200 - 2300 MHz (S band) are 89 channels with 1 MHz bandwidth each *).

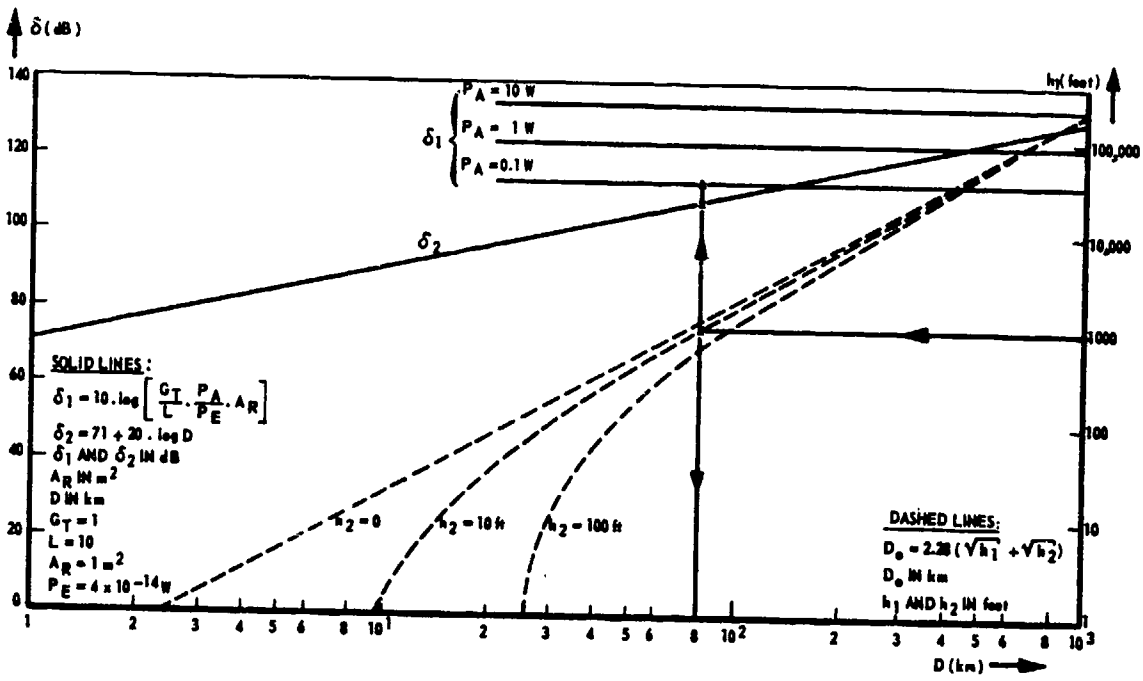


Figure 10.7 Simplified propagation design chart

*) The use of the P band was only allowed until January 1st, 1970. Unfortunately, however, the transmitters and receivers for the L band and S band are at present still much more expensive than those for the P band. Besides, the size and the weight of the airborne L band and S band transmitters are higher compared to the P band equipment. Mainly because of these reasons the switch-over to the L band and S band channels has not yet been completed.

The higher the frequency of an electromagnetic wave, the more its propagation resembles that of light. The usuable range between the airborne and the ground terminals is limited by the line of sight if, in a first approximation, the diffraction is neglected. For L and S band frequencies this can be done with good approximation. Within the line of sight the formula for wave propagation in free space is a good approximation, provided the heights above ground of the transmitting and the receiving antennas are at least several wavelengths.

The line of sight D_o can be calculated by using the formula

$$D_o = 2{,}28\,(\sqrt{h_1} + \sqrt{h_2}) \tag{10.4}$$

where D_o = the distance in km

h_1 = the height of the transmitting antenna (in the aircraft) in feet

h_2 = the height of the receiving antenna above the ground in feet.

For three different heights h_2, this formula has been displayed in Fig. 10.7 by the dashed lines. Good data reception can only be expected for distances D between aircraft and ground station satisfying the condition

$$D \leq D_o \tag{10.5}$$

Within this range the required radiated transmitter power can be estimated by using the solid curves in Fig. 10.7. Two auxiliary parameters δ_1 and δ_2 are used. In a logarithmic scale we have

$$\delta_1 = 10.\log \frac{G_T.P_A.A_R}{L.P_E} \tag{10.6}$$

$$\delta_2 = 71 + 20.\log D \tag{10.7}$$

G_T is the gain of the transmitting antenna, L the product of losses (cable, mismatching, minima of radiation pattern), P_A and P_E are the transmitted power and the required minimum receiver input power respectively for a given telemetry system, A_R the effective area of the receiving antenna in square meters and D is the distance between the antennas in km. δ_2, measured in decibels, indicates the attenuation of the transmitted wave as a function of the distance D. In order to obtain good reception, this attenuation must be overcome by δ_1, which contains those parameters which are independent of the distance D.

Thus a supplementary condition to equation 10.5 is

$$\delta_1 \leq \delta_2 \tag{10.8}$$

The plot of eq. (10.6) in Fig. 10.7 is based on the parameters $G_T = 1$; $L = 10$; $P_E = 4.10^{-14}$W (correct for FM/FM systems); $A_R = 1\ m^2$ and transmitter powers P_A of 0.1 W, 1 W and 10 W. This is roughly equivalent to the practical conditions. Often instead of the effective area of the receiving antenna its gain G_R is specified. Then, A_R can be calculated by using the formula

$$A_R = \frac{G_R.\lambda^2}{4.\pi} \tag{10.9}$$

λ is the wavelength.

The use of Fig. 10.7 will be made clear by the following example: For a height of the aircraft of 1000 feet and a height of the receiving antenna of 3.3 m (10 feet), the line of sight is 80 km. With the above-mentioned assumptions we have at this distance a safety margin of 5 db even with a transmitter power of only 0.1 W. This safety margin may be sufficient when using a ground station with diversity reception capabilities (see below). Otherwise, a transmitter power of 1 W would be required in order to overcome fading effects, which are not taken into account in Fig. 10.7.

One of these fading effects is the so called fading due to multipath propagation. Sometimes the antenna not only receives the wave coming directly from the transmitter but also a reflected wave (reflected from the ground or from buildings), the phase of which is shifted with respect to the direct wave. Depending on the heights and the distances of the antennas the phase shift may reach 180°. Thus the received signal power may from time to time decrease considerably.

It should be mentioned also that the curve $\delta_2(D)$ at the limit of the line of sight is too optimistic. Beyond this limit the wave-attenuation increases very rapidly. Therefore, little or no increase in range can be obtained even if the transmitter power is substantially increased. On the other hand, the example shows that within the line of sight reliable communication with relatively low transmitter power is possible.

An effective way to overcome the difficulties caused by fading is to use diversity reception techniques. This technique uses two rf receivers (see Fig.10.1). Each receiver is connected to a separate antenna, which picks up waves of different polarization (polarization diversity), of different frequencies (frequency diversity) or at different locations (space diversity). The drawback of the frequency diversity method is that it requires the additional bandwidth for a complete second rf channel. A predetection or postdetection combiner at the output of the receivers combines the weighted sum of both input signals. The weighting coefficients are controlled by the signal-to-noise ratio of the two inputs, in such a way that the coefficient approaches 1 for a good signal and 0 for a bad signal. Because of the different conditions of wave reflection it is not very probable that a loss of signal occurs at both inputs simultaneously. The probability of good reception, therefore, is substantially increased.

The on-board transmitting antennas are mounted in a fixed position with respect to the vehicle. The axes of these antennas may, therefore, have different directions with respect to the ground during a flight. Therefore, an omnidirectional radiation pattern is desirable but cannot be achieved exactly. The free-space radiation patterns of the antenna systems that can be used on aircraft always show minima. In addition, the aircraft itself distorts the radiation pattern. Parts other than the antenna may reradiate signals (parasitic radiation) which will interfere with the original signal. Furthermore, at some attitudes of the aircraft, the wing or the fuselage may intercept the radiation to the ground station (shadow effects). Therefore, the layout of the airborne antennas must be done very carefully, taking into account the expected attitudes of the aircraft during flight.

The airborne antennas are often $\lambda/4$-stub or blade antennas, which have a linear polarization. Most of the ground receiving antennas are circularly polarized in order to obtain a reception independent of the orientation of the airborne antenna. Turnstile or helical antennas are used for the P band frequencies; circularly polarized feeds with a parabolic reflector are preferred for the L band and S band frequencies. For the latter frequencies higher gains G_R must be used than for the P band frequencies in order to get the same effective antenna area A_R. This is shown by eq. (10.9). The wavelength λ of the L band is about 1/6 and of the S band about 1/9 of that of the P band, respectively. As a result of the higher gain the directivity is higher, so that problems with manual tracking of the receiving antennas occur, especially with aircraft which fly at high speed near the ground antenna (high angular velocity). Therefore, automatic tracking (e.g. monopulse tracking) often is preferred, despite the higher complexity of the ground station.

At the receiving end of the telemetry link double superheterodyne receivers with plug-in techniques are mostly used. Therefore, the receivers can easily be matched to different telemetry systems by choosing the proper tuning heads, intermediate frequency filters, and rf demodulators. In order to obtain good receiver input sensitivity (low value of P_E in equation (10.6)) the noise figure of the receiver must be kept low. A low-noise preamplifier situated at the antenna is recommendable, if it is not possible to locate the antenna near the receiver. The low noise figure of the preamplifier then determines the noise figure of the receiving system. Reception of L band and S band frequencies can be done with special tuning heads, which are available for standardised telemetry receivers. Alternatively, a frequency down-converter may be mounted at the antenna which converts the L band or S band frequencies to the P band. Then the existing P band equipment can still be used.

Most telemetry receivers can be equipped with an accessory unit for postdetection or predetection diversity combining. Both methods are treated in the next section in some more detail.

10.4 GROUND RECORDING AND DISPLAY

The recovered data signals must be displayed for quick look in the ground station and stored for subsequent data processing. Quick-look display usually is done with pointer instruments as well as with strip-chart recorders and X-Y recorders. Data signals containing frequency components higher than 100 Hz must be recorded by oscillographic recorders. These paper recorders have the advantage of being both a

display and a storage equipment. On the other hand, the storage capacity does not meet the high requirements of modern flight tests. Moreover, the stored information can only be converted back into an electrical signal with great difficulty. Thus, subsequent data processing is restricted.

In this connection magnetic tape recorders have excellent properties (see Chapter 9.4, Ref. 8), and they are therefore standard equipment in telemetry ground stations. A few years ago postdetection recording was mainly used, in which the frequency-multiplexed signal (FM/FM system) or the time-multiplexed signal (PDM/FM, PAM/FM and PCM/FM system) at the output of the demodulator is recorded on one track of the tape recorder in the direct mode or in the FM mode. The demultiplexing is done during playback. This method allows the recording of a great many data channels. It is also possible to do the demultiplexing on-line, so that the individual data signals are immediately recorded on different tracks of the tape recorder. This method is limited by the maximum number of tracks that can be recorded simultaneously in the ground receiving station.

Recently, predetection recording has become more important. The availability of recorders with continuous recording capabilities up to frequencies of 2 MHz allows the direct recording of the receiver intermediate frequency (third I.F.; maximum 900 kHz; see Ref. 6) prior to demodulation. The main advantage is that the operation and maintenance of ground stations is simplified, especially for those using several telemetry methods (FM/FM; PDM/FM; PAM/FM; PCM/FM). This is the case, because the recording method is the same regardless of the type of multiplexing used. In postdetection recording, on the other hand, the recording method (direct recording or FM recording) must be matched to the type of multiplexing. In addition, it is advantageous to record the signal as early in the transmission chain as possible. The optimization of the playback channel with respect to the signal-to-noise ratio (e.g. varying the I.F. bandwidth and consequently the demodulator threshold) need not be done prior to reception but can be attempted later by repetitive trial and error. In other words, in postdetection recording the I.F. bandwidth must be chosen before the test on the basis of an expected rf signal bandwidth. Normally a higher standardized I.F. bandwidth is used. Under bad receiving conditions, however, the signal-to-noise ratio S/N may become too low and consequently a loss of data can occur. In predetection recording the I.F. bandwidth can be decreased before playback in such a way, that the S/N ratio is raised to a certain extent.

10.5 COMPARISON OF IRIG-STANDARDIZED TELEMETRY SYSTEMS

A comparison of the IRIG standardized telemetry systems is made in Table 10.1 on the basis of 5 different principles. IRIG standardized telemetry systems are well-established, proven and available on the market at reasonable prices. They are suitable for almost all measuring problems.

Accuracy: The accuracy of modern analog systems, when carefully adjusted, approaches $\pm$ 1 % (see Ref. 8). The accuracy of the twofold multiplexing in the case of the PAM/FM/FM system can be $\pm$ 2%. PCM/FM is capable of almost any required accuracy. The only limitation is the accuracy of the transducers and the A/D converters used in the system.

Maximum number of data channels: As discussed in Section 10.2 the systems using time division multiplexing have the highest capacity in number of channels.

Maximum information rate (I.R.): In Table 10.1 the I.R. is given in bit/sec. In the case of the analog systems the I.R. is calculated from the significant amplitude resolution and the sampling theorem (see Ref. 8). The PAM/FM system and the PCM/FM system can handle the highest I.R., followed by the FM/FM system. Comparatively, PAM/FM/FM and PDM/FM can handle only very poor information rates.

Flexibility: Flexibility is very good for systems using time-division multiplexing (see Section 10.2). Subcommutation and supercommutation can be used to adapt the system to requirements for the number of channels and for frequency response. In the case of PCM/FM it is also possible to use different word lengths for the individual parameters; the individual channels can thereby be adapted to the accuracy of each parameter.

Utilisation of radio frequency power and bandwidth: These aspects are covered in detail in Ref. 9. It has been found, that in the case of high accuracy requirements PCM/FM is the best method for transmitting data with a certain information rate through a band-limited rf channel with minimum rf power. In the case of moderate accuracy requirements PAM/FM requires minimum bandwidth. The widespread FM/FM method is not as good and the PAM/FM/FM method has only poor features in this respect. In the latter

Table 10.1 Comparison of IRIG - Standardized Telemetry Systems

Principles of comparison	I FM-FM proportional bandwidth	II FM-FM constant bandwidth	III PAM-FM-FM	IV PAM-FM	V PDM-FM	VI PCM-FM
Accuracy (careful adjustments presupposed)	$\pm 1\,\%$ (M = 5)*	$\pm 1\,\%$ (M = 5)	$\pm 2\,\%$	$\pm 1\,\%$	$\pm 1\,\%$	Limited by accuracy of transducers or A/D converters only
Maximum number of data channels	19 (VHF band) 21 (UHF band)	15 (VHF band) 21 (UHF band)	128 without subcommutation. Can be expanded most effectively by subcommutation	See III	90 without subcommutation. Can be expanded most effectively by subcommutation	Depends on word length. Frame length max. 2048 bit. In practice, all requirements can be met by super- and subcommutation
Maximum total information rate (sum of all channels)	VHF band: $65 \cdot 10^3 \frac{bit}{sec}$ (M=5)* $270 \cdot 10^3 \frac{bit}{sec}$ (M=1) UHF band: $110 \cdot 10^3 \frac{bit}{sec}$ (M=5) $460 \cdot 10^3 \frac{bit}{sec}$ (M=1)	Nearly the same as I	$16700 \frac{bit}{sec}$ (channel F)**	VHF band: $3.6 \cdot 10^5 \frac{bit}{sec}$ UHF band: $1.8 \cdot 10^6 \frac{bit}{sec}$	$22 \cdot 10^3 \frac{bit}{sec}$	VHF band: $2 \cdot 10^5 \frac{bit}{sec}$ UHF band: $1.2 \cdot 10^6 \frac{bit}{sec}$
Flexibility (number of channels; channel cut-off freq.)	Moderate (fixed subcarrier frequency allocation; only a few variations in channel bandwidth)	See I	Good (low data frequencies presupposed)	Good	Good (low data frequencies presupposed)	Excellent (sub- and supercommutation, variable word length)
Utilization of radio frequency power and radio frequency bandwidth	Moderate	See I	Poor (can be tolerated as the power requirement and the bandwidth is low because of the low information rate)	Good (optimal for moderate accuracy requirements)	Good	Good (optimal for high accuracy requirements)

VHF band: P band UHF band: L and S band * M = Modulation Index of FM carrier ** Channel with the highest bandwidth of the FM proportional bandwidth subcarrier pattern

case, however, the poor features can be tolerated, as the system carries only a low information rate. Normally it is used in addition to a FM/FM system. Then, the features of the combined system are determined by that of the FM/FM method.

10.6 ON-LINE DATA PROCESSING

As the data measured in the aircraft are immediately available in the ground station, telemetry makes it possible to observe the measured parameters while the flight is in progress. Until recently this on-line processing and display was mainly used in critical phases of the flights only. In the latest flight tests with military and civil prototypes telemetry and associated on-line processing is being used in all flight test phases and for the majority of the parameters. Although on-board recording is still used as a standby in case telemetry data are lost, there is a tendency to do most of the analysis from the on-line displays fed by telemetry. Thus, modifications to the flight test programme can be made during flight. Experience has shown that this can reduce the number of flights required in a test programme by 30% or more.

The general considerations about data processing are discussed in Chapter 12. Here a few remarks will be made about on-line computing.

Analog computing methods are very useful means of on-line data processing, especially if the number of channels is not very large. They combine high speed of computation with good adaptability of the hardware to individual problems. The accuracy is usually not very high. But in many cases a sufficient accuracy can be obtained, especially for quick-look display. An example for a relatively simple application is the computation of indicated airspeed, true airspeed and Mach number from the measured data, total pressure, static pressure and temperature. About seven operational amplifiers, two multipliers and two square-root function generators are required.

Digital computing has a number of advantages over analog computing, for instance:

- the computation accuracy can be as high as is justified by the accuracy of the input data
- integration can be done without drift (analog integration shows a drift which increases with time)
- storage specifications are better (quick access, arbitrarily long duration)
- the digital computer can be more readily used for making logical decisions, such as detecting that a signal or a combination of signals has exceeded a certain limit value
- in a more sophisticated application several measured parameters can be used as an input to a model; the output of the model is compared to other measured parameters and if the difference is too large a special programme is initiated
- the computer can also be used for several tasks in the ground station (such as decommutation of PCM signals) and for automatic control tasks in the ground station (automatic control of the receiving antenna, automatic search patterns with high-directivity antennas, switch-over to autotracking when acquisition is obtained etc.).

A problem with digital on-line computing is that the time required for all computations must be less than the time between two successive data samples. Even very fast computers reach this limit very quickly when handling complex problems.

Hybrid computing may be, to some extent a solution to this problem. By combining an analog computer and a digital computer, the computing programme can be divided into two parts, making optimal use of the advantages of both methods. The interface between the two computers consists essentially of analog-to-digital and digital-to-analog converters. The programming of a hybrid computer is, however, very difficult.

10.7 REFERENCES

1. M.H. Nichols, L.L. Rauch — Radio Telemetry, John Wiley and Sons, Inc., New York, N.Y., 2nd Edition, 1956.
2. H.L. Stiltz (Editor) — Aerospace Telemetry, Volume 1, Prentice-Hall, Inc., Englewood Cliffs, N.J., 1961.
3. H.L. Stiltz (Editor) — Aerospace Telemetry, Volume 2, Prentice-Hall, Inc., Englewood Cliffs, N.J., 1966.

4. L.E. Foster — Telemetry Systems, John Wiley and Sons, Inc., New York, N.Y., 1965.

5. E.L. Gruenberg (Editor-in-Chief) — Handbook of Telemetry and Remote Control, McGraw-Hill, Inc., New York, 1967.

6. — Telemetry Standards, IRIG Document 106-71.

7. A. Becker — The Role of Telemetry in the Modern In-Flight Measuring Technique, presented at the 26th AGARD Flight Mechanics Panel Meeting, Paris, 1965.

8. A. Becker, B. Gartung, H. Meyer — Comparison of Systems, presented at the 30th AGARD Flight Mechanics Panel Meeting, Montreal 1967, AGARD Conference Proceedings No. 32.

9. — Aeronutronic Inc., Division of Ford Co., Newport Beach, Calif. Telemetry System Study, Final Report, Vol. I - III, ASI Publication No U-743, 1959. (Summary in Ref. 5, Chapter 9, Section 4).

CHAPTER 11
GROUND-BASED EQUIPMENT

by

O. Weber

11.1 INTRODUCTION

In modern flight testing most measuring equipment is carried on board the aircraft. For some types of test, however, ground-based equipment is used, often in combination with airborne measurements. Besides telemetry receivers, which are discussed in chapter 10, the most important type of measurement made from the ground is trajectory measurement. Although there is a tendency towards measuring aircraft trajectories in the aircraft itself (for instance by using inertial platforms), trajectory measurements from the ground are still commonly used. Typical applications are: take-off and landing performance measurements, analysis of the effect of improvements in radio navigation systems and auto pilots for the reduction of landing minima during bad weather conditions, analysis of flight performance during critical phases of the flight such as superstall, measurement of hovering and transition performance of VTOL aircraft, analysis of the performance of parachutes and ejection seats, etc.

There are a few test ranges which have extensive, permanent equipment for measuring aircraft trajectories. Most trajectory measurements are, however, made with mobile equipment. This requires careful planning and often improvisation. This chapter will primarily describe such mobile operations. More detailed discussions of trajectory measurements are given in References 1, 2, 8 and 9, which also give lists of other references.

An important aspect in the use of ground-based equipment is time synchronisation with recordings made on board the aircraft. This will also be discussed in this chapter. Although time synchronization is discussed here in the context of ground-based measuring equipment, the principles given here also apply to synchronization between two or more recording systems in the aircraft.

11.2 CAPABILITIES OF A TRAJECTORY MEASURING SYSTEM

The usual trajectory measuring systems like kinetheodolites, radars and interferometers (Ref. 1, 6, 8, 9 and 11) primarily determine the direction from the instrument to the target and/or the slant range. The co-ordinates and the velocity of the target in an earth-fixed reference system can be derived as a function of time from the measured data. Because three co-ordinates for the position of the target are necessary, at least three independently measured values have to be determined as a function of time.

11.2.1 Co-ordinate systems

The setting up of a mobile trajectory measuring station requires a number of special preparations:

1. The position of the trajectory measuring system has to be surveyed.
2. Computer programs for the transformation of the measured data to the reference system have to be written and tested.
3. In special cases, the proving ground has to be surveyed additionally, for instance for the calibration of radio altimeters.

The technical and scientific effort, and therefore also the duration and cost of the preparations, depend on the requirements of the reference system. For the determination of the trajectory of a parachute, only the direction of gravity and a rough statement of the north direction (for taking the wind into account) are necessary. If, however, a navigation system like VOR or LORAN with a far distant reference station or base-line is used together with the ground-based equipment, a relation between the positions of the trajectory measuring systems and the navigation system has to be established.

For facilitating the analysis, the co-ordinate system in which the results of the trajectory measurement are presented should be chosen so that the most important parameters of the flight trajectory are measured along the co-ordinate axes. Therefore, in the case of take-off and landing measurements, one axis of the co-ordinate system should coincide with the centre line of the runway and another should be vertical.

11.2.2 Determination of the velocity vector

The components of the velocity vector are usually derived from the time sequences of the co-ordinates of the targets by means of a differentiation process. In its simplest form this differentiation can be done by dividing the differences between successive points of the trajectory by the time interval between them. This process produces a large scatter in the velocity results, because of random errors in the measured values. It is therefore better to smooth the data first.

Smoothing can be done by the computer, using the methods described in Chapter 12. It is also possible to have a skilled operator approximate the points by a smooth curve. He can take into account the physically possible trajectory. The importance of this graphical method should not be underestimated. It is very difficult to match the skill of an operator even by sophisticated computer algorithms. This method has, however, the disadvantage that the trajectory data have to be digitised again before they can be used in the digital computer. A combination of the automatic and manual smoothing is often preferable. Then the operator takes out the blunder errors and presents these as corrections to the computer. The random errors are then smoothed by the computer from the corrected input.

When smoothing is required the sampling rate should be higher than would be required to reduce the aliasing errors to an acceptable level (see Chapter 6). The smoothing becomes more accurate as more redundant data are available although the increase in accuracy diminishes with increasing redundancy. The sampling rate should, therefore, be carefully chosen.

The differentiation can then be done from the smoothed data points. In many cases the velocity data will be smoothed again before being presented.

11.3 SELECTION OF THE TRAJECTORY MEASURING SYSTEM

Usual trajectory measuring systems are: kinetheodolites, phototheodolites, laser ranging equipment, IR trackers, tracking radars, electronic interferometers (AME, angle measuring equipment) and continuous wave ranging instrumentation (DME, distance measuring equipment) (Ref. 1, 6, 8, 9 and 11). The two last systems generally are only suitable for permanent ranges, because of their complicated antenna systems. Phototheodolites, laser ranging equipment and IR trackers are used as trajectory measuring instruments for a few special tasks such as low level flights or take-off and landing tests.

The two most important mobile trajectory measuring systems with a broad spectrum of applications are kinetheodolites and tracking radars. The discussion of these two methods will show the considerations for choosing a system which is optimal for the planned flight test.

11.3.1 Kinetheodolites

A kinetheodolite records the azimuth and elevation of the optical axis of the theodolite and shows the displacement of the target from the optical axis on the film picture (Ref. 1, 6 and 11). These four values are separately read out and combined into two values, the azimuth and elevation of the target. Therefore, at least two separate kinetheodolites are necessary for the determination of the three co-ordinates of the target (Fig. 11.1). However, three separate stations are desirable for increasing the reliability.

Advantages:

- The systematic and random errors can be kept below 0.01 degree, if the acceleration of the kinetheodolite is within reasonable limits (Ref. 3, 4 and 12).

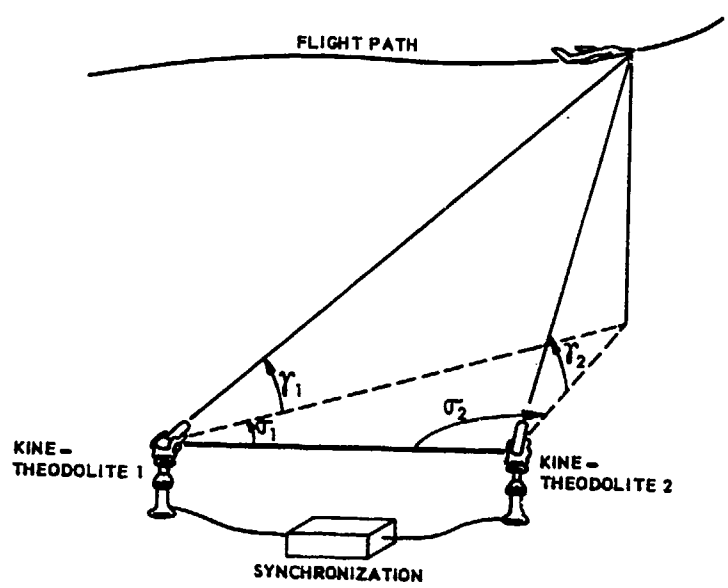


Figure 11.1 Trajectory measurement by means of two kinetheodolites

This equipment is, therefore, suitable for absolute measurements. The reference points on the aircraft must be well defined.

- The initial cost and amortization of this system are lower than for a tracking radar, if the tracking device of the kinetheodolite is simple and only a film is used for data storage.
- Targets on the ground or in the vicinity of the horizon can be measured, as well as those at higher elevations.
- The kinetheodolites photograph the target at each measurement, and thus valuable additional information is obtained which often renders the employment of another camera unnecessary, and which can facilitate the synchronization problem discussed in detail in Sections 11.6 to 11.8. Examples of additional information are external events such as the separation of a parachute, or a rough estimate of the attitude of the target.

Disadvantages:

- The ground survey for the stations is expensive (two or three separate kinetheodolites).
- Several operators are necessary during the measurement.
- Targets near the zenith can lead to intolerably high angular velocities.
- The target must be acquired and tracked visually by the operators.
- The slant visibility is an upper limit and the acquisition range, particularly for high speed aircraft at large distances, will be somewhat smaller than the slant visibility. Slant visibilities below 10 km are common in Central Europe. Even if the slant visibility is much higher, the acquisition range is often below 10 km for an aircraft whose flight path in the sky is not well known. Much better acquisition ranges can be achieved in a desert, as at the test centers in New Mexico. The recognition of an aircraft in twilight or at night can be significantly increased when continuously radiating lamps or flash lights are mounted in the aircraft. Their installation, including power supply, has to be planned in time.
- The processing of kinetheodolite measurements using classical methods is expensive and tedious. The reading of the azimuth, elevation and displacement stored on one frame of kinetheodolite film will take at least one minute. Appreciably higher rates of reading are possible when kinetheodolites with digital presentation of elevation and azimuth are used together with special semi-automatic reading equipment. For the reading it is necessary to choose a reference point on the aircraft, which is recognizable on every frame. This may, for example, be the rudder of the aircraft or a wheel of the landing gear. Most well identifiable reference points have the disadvantage of not coinciding with the center of gravity or another important point of the aircraft. The transformation from the employed to the desired reference point, however, depends on the attitude of the aircraft. In some cases, transformation difficulties can be decreased by putting strikingly coloured marks in the vicinity of the desired reference points. This is, however, only effective at relatively short ranges. On-line storage and processing of azimuth and elevation of the optical axis is an integral part of modern kinetheodolites, but this problem has not yet been solved for the displacement of a target with a complex pattern.
- In some modern kinetheodolite systems the azimuth and elevation angles of the optical axis are stored in electrically retrievable form, so that they can be processed automatically. Even with such systems, the displacement of the aircraft from the optical axis must be measured manually from the film picture.

Range of applications:

- Kinetheodolite systems are ideal for measuring the trajectory of targets near the horizon or on the ground. Targets at small or medium slant ranges can be measured with high absolute accuracy if the slant visibility is satisfactory.

11.3.2 Tracking radar

A tracking radar automatically tracks the target during the measurement and measures the azimuth, elevation and slant range of the instantaneous center of reflection of the target (Ref. 1, 6, 8, 9 and 11). As three co-ordinates are measured, only one tracking radar is necessary for the determination of three co-ordinates of the target.

Advantages:

- The target can be acquired and tracked even if it is masked by fog or many kinds of clouds.
- Large slant ranges are possible.
- Only one radar is necessary.
- The ground survey is simple and cheap.
- Two operators are often sufficient during the measurement.
- On-line data storage and processing is common procedure.
- The error of the slant range can be kept low and nearly independent of the range (about ± 10 m) without high costs.

Disadvantages:

- Targets on the ground or in the vicinity of the horizon cannot be tracked.
- The reference point on the target is random for skin tracking. By the addition of a transponder to the aircraft, not only the reference point can be better fixed, but also a considerably larger range can be obtained; however, difficulties in installing the antennas have to be overcome. The range of a typical radar is about 30 km (diameter of the aerial 1 m, X-band, peak power 40 kW, skin tracking of a medium or large aircraft), but ranges up to 250 km are obtained by some fixed tracking radars.
- The angular errors are small only for high precision radars, but these are very expensive. The calibration of the elevation angle of a radar is difficult.
- The systematic error of a tracking radar, which has the above-mentioned characteristics, is of the order of 0.1 degree. High precision radars sometimes have errors which are an order of magnitude smaller. The random error depends on the distance and the size of the target and can be as low as the systematic error, if the apparent size of the target is small.
- A target cannot be tracked in the neighbourhood of a second target of comparable or larger size.

Range of application:

- Tracking radars are ideal for determining the trajectory of targets at medium or large ranges under nearly all weather conditions. The effect of angular errors has to be considered.

11.4 OPTIMAL POSITION OF THE TRAJECTORY

Rough estimates of the systematic and random errors of kinetheodolites and tracking radars have been mentioned in Section 11.3. The flight test engineer is not only interested in the accuracy of the original measured values, but especially in the accuracy of the trajectory of the target derived from them. Here the geometry of the trajectory of the target relative to the measuring system is of decisive importance for the success or failure of an exact determination of the position or the velocity vector of the target. The starting point for these considerations is the concept of the error field (Ref. 1, 3, 6, 7 and 10). This is strictly valid only for measurements free of bias errors. If only the velocity vector of the target or the relative position of two trajectory points to each other is of interest, bias errors can be neglected in the first approximation and the concept of the error fiels yields useful results.

If the original measured values (angles and/or slant range) only show normally distributed random errors, then for each point of the trajectory an error pattern can be indicated. In the three-dimensional spatial case it is an ellipsoid; in the two-dimensional plane case it is an ellipse with the trajectory point in the centre. The probability that the target lies on the ellipsoid or the ellipse is equal for all points of this error pattern. Figure 11.2 and 11.3 show

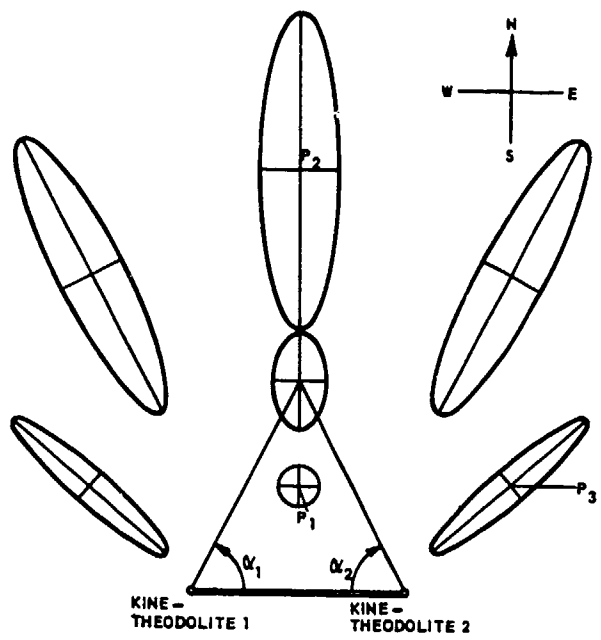


Figure 11.2 The error field for measurements with two kinetheodolites at relatively low elevations

the error ellipses for several points of the measuring range of a kinetheodolite system consisting of two stations and for a tracking radar.

The error field for measurements with two kinetheodolites (Fig. 11.2) shows that there is only one point P_1 where the errors in all directions are the same. At the point P_2, also on the line of symmetry but farther away, the accuracy in the East-West direction is much greater than that in the North-South direction. At point P_3 the ratio between the axes of the error ellipse is even more extreme. It will be clear that if the main interest in the test is in the along-track positions and velocities, then a flight path parallel to the connecting line between the theodolites will give optimum results; the distance from this connecting line should be such that the maximum rate of change of the azimuth angle does not become too large. If the main interest is in the lateral deviations from the nominal flight path and in the lateral velocities, then the flight should be conducted along the line of symmetry between the two theodolites.

The error field of a tracking radar (Fig. 11.3) is different from that of the kinetheodolite. As the error in the range measurement is, in a first approximation, independent of the range, the errors in the radial direction at points P_1 and P_2 are about equal. The errors in the tangential direction increase proportionally to the range. The error field is rotationally symmetric, so that the accuracy of the measurement is independent of the azimuth of the target.

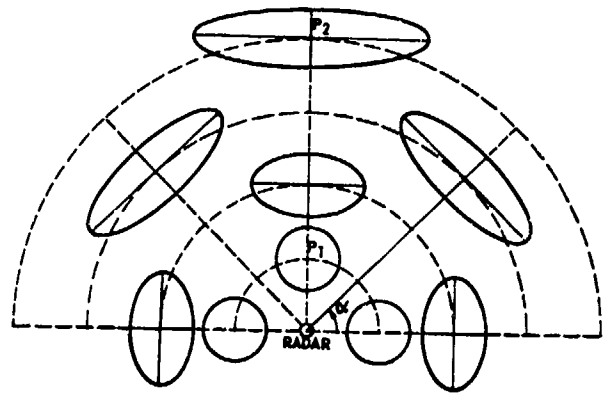


Figure 11.3 The error field for measurements with a tracking radar at relatively low elevations

If optimal accuracy must be obtained over a large range, it can be useful to combine optical and electronic trajectory measuring systems.

11.5 TAKE-OFF AND LANDING MEASUREMENTS

There are many methods for measuring take-off and landing performance. In some of these methods only ground-based measuring equipment is used, in others only airborne equipment, and in a few a combination of airborne and ground-based measuring equipment. It is not the purpose of this chapter to describe all these methods. A volume on this subject will appear later in the AGARD Flight Test Instrumentation Series. Here we will only discuss a few applications of the principles discussed in the previous sections to one of these methods: that using ground-based kinetheodolites or special take-off cameras.

The trajectory to be measured is nearly always two-dimensional: the aircraft will follow the runway centre line and only measurements in the vertical plane through that centre line are of interest (see Fig. 11.4). These can be made by a single kinetheodolite, placed beside the runway at about the middle of the trajectory to be measured. As the range of elevations generally is small, it is often possible to keep the aircraft in sight without moving the optical axis of the camera in a vertical direction. Many special take-off cameras, therefore, can only move about a vertical axis. It will be clear that for such a system the data processing time will be much less than would be required by a system using two kinetheodolites with free movement about two axes.

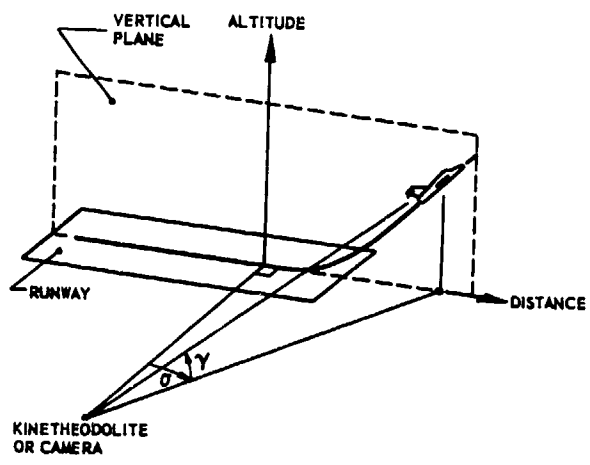


Figure 11.4 Take-off and landing measurements with one kinetheodolite or camera

If the aircraft should deviate from the vertical plane through the runway centre line, the method described above will produce an error in the measured longitudinal position of the aircraft. This error will be large when the azimuth angle σ (Fig. 11.4) approaches 90 degrees. The camera should, therefore, be as far from the runway centre line as is possible for obtaining the required accuracy. This required accuracy is generally not very high. The measured results will have to be reduced to standard meteorological conditions (direction and velocity of wind, pressure, temperature, humidity) and these corrections are not very accurate. Also it must be realised that the pilot cannot always take off and land in the same manner. The method described above will, therefore, often produce satisfactory results at a relatively low price.

11.6 TIME AND TIME STANDARDS

The purpose of combined ground-based and onboard measurements is to determine the parameters of the aircraft and of the environment as a function of time, for example position and static pressure. Then the time bases of the airborne and ground recorders must be co-ordinated. The principal aspects of such a time co-ordination system are:

1. frequency standard
2. reference point of the time scale
3. time format
4. synchronisation
5. reliability and interference.

The time scale is, in general, derived from a frequency standard such as a quartz oscillator or an atomic oscillator (Rubidium or Cesium) (Ref. 1, 5 and 6). If a single frequency standard is used for the total measuring system, the accuracy of the frequency standard need not be very high. Only the time interval between two consecutive measurements is determined by the frequency standard. A frequency error, therefore, only affects the accuracy of the first derivative of the measurement, for example the velocity of the target or the rate of climb. An accuracy of one part in 10^5 is easily maintained by a simple quartz crystal oscillator. This is higher than the accuracy usually needed for parameters such as velocity. Tests of inertial components may be an exception.

The reference point of the time scale is in general not important. Any local time scale can be used. Exceptions are, for example, co-ordinated measurements with a LORAN C-system or a calibration with the stars as a reference system. The position of the stars and the pulses of LORAN C are referred to Greenwich Mean Time. Therefore, the reference point and sometimes also the frequency of the timing system must be co-ordinated with Greenwich Mean Time.

If more than one frequency standard is used for a long flight test, the accuracy of the frequency standards must be much higher. A difference of one part in 10^5 between two standards leads to a difference between the reference points of 0.1 sec after about three hours. The state of the art is such that high quality (1 part in 10^8) frequency and time standards of small size and low weight are commercially available. The standards can be adjusted so that they differ at most by 1 millisecond after a time interval of several hours. If one time standard is used on the ground and another on board, these two standards can be compared directly with each other before and after the flight test. If the direct comparison between airborne and ground-based standards is difficult, both standards can be synchronised by radio before and after the flight. In some cases no special radio link is necessary. In some areas with a good time signal broadcast (Ref. 5 and 6), it is sufficient to receive the time signals with inexpensive receivers and to use them for adjusting the time standards, provided that the receivers have the same time constants. The time constants of commercially available VLF receivers can be greater than 1 msec and can differ considerably even in receivers of the same type.

The chosen time format affects to a high degree the cost and the reliability of the timing system. Modern types use pulse trains which contain the complete time information in a coded format, for instance the IRIG code B system (Ref. 1 and 6). If the transmission or recording of the pulse trains is disturbed for a short time, this does not lead to a loss of time scale because the next undisturbed pulse train contains the complete time information. These fully coded systems are rather expensive, both in initial cost and in bandwidth (they usually require a separate track in each recorder). Their application in continuous trace recorders presents special problems. These are some-

times solved by equipping the recorder with a device which can print numbers on the paper or film.

For many flight tests a simpler time format can be used. In the simplest type marks are recorded periodically, for instance every second. Then the time co-ordination of the marks in the different recorders must be obtained by other means, as described in Section 11.8.2. This method has the disadvantage that the time co-ordination must be established anew if a few pulses have been lost. When using these simpler systems, but also in the case of time-coded systems, one should be sure to note rough time information such as flight number, date and the indication of a regular clock on all records. In the case of quasi-steady processes, these notes alone may be satisfactory for an evaluation of the data.

11.7 SYNCHRONIZATION OF TRAJECTORY MEASURING SYSTEMS

Large trajectory measuring systems like kinetheodolites and tracking radars usually have complete timing and synchronisation equipment. As this equipment often is not very flexible because of optical or mechanical reasons, its features are important for the co-operation with other ground-based or on-board instrumentation.

If more than one measuring station is employed, for instance two kinetheodolites, the best solution is to have the measurements at both stations completely synchronised by triggering them at regular intervals from the same time base. This greatly simplifies the data processing. The tolerable synchronisation error should be considered before the flight test, in order to save unnecessary technical effort and cost. For example, high speed aircraft (Mach number ≈ 1) fly a distance of about 1 m in 3 milliseconds. If the intersection of the rays from the kinetheodolites to the target is rectangular and one kinetheodolite is delayed by 3 milliseconds with respect to the other, the error in the computed position is 1 m. The position error can be larger due to an unfavourable geometry of the trajectory relative to the ground-based measuring system.

The propagation time of the signals may affect the synchronisation. The range of the trajectory measuring systems used in flight tests seldom exceeds 60 km. The electromagnetic waves propagate in the atmosphere at about $3.\ 10^5$ km/sec. The propagation times of light from the aircraft to the optical trajectory measuring systems and of the radio signals from the transmitting antenna of the timing centre to the receiving antennas of the trajectory measuring stations usually are less than 0.2 msec. and can therefore often be neglected. The effect of propagation delays in transmitters and receivers must be determined separately for each system.

The method used in many of the simpler kinetheodolite systems (Ref. 1, 6 and 11) is that the pulses from the synchronisation unit trigger both kinetheodolites and at the same time actuate a counter in each kinetheodolite. On the film, the frame number given by this counter is recorded together with the azimuth and elevation angles and the picture of the target. The frame number is then regarded as the measure of time. This synchronisation will be wrong if one or more kinetheodolites and/or counters miss pulses or are actuated by spurious pulses. If these events are few in number, it is often possible to reconstruct the synchronisation and the time scale because the trajectory must not show discontinuities and some redundancy is present (four angles for three co-ordinates). This is in general difficult and tedious. Equipment for the synchronisation of trajectory measuring systems should, therefore, be very reliable and should not be influenced by external interference. Modern types of trajectory measuring systems already satisfy these requirements. Here the use of single pulses for synchronisation is avoided, but use is made of e.g. the IRIG code B.
The pulse trains are also recorded. The resolution of the pulse trains for the measuring time can be less than the synchronisation accuracy, because they are only necessary to distinguish consecutive measurements.

11.8 SYNCHRONIZATION OF GROUND-BASED AND AIRBORNE MEASURING EQUIPMENT

The purpose of using ground based and airborne measuring systems simultanously is to derive correlations between the measured quantities. Therefore, it is necessary to have all parameters in a common time scale. Two main methods can be distinguished:

1. Exact synchronisation by technical means, with
   a. separate time bases
   b. one common time base

2. Synchronisation by interpolation, with
   a. random sampling
   b. correlated measuring times

It largely depends on the purpose of the flight test, the type of the available measuring and recording devices and the data processing methods, which method will be used for the synchronisation. Emphasis can either be placed on the engineering aspects of the synchronisation equipment or on the data processing. In general, it is not necessary to synchronise the trajectory measuring system with the airborne measuring system or with other ground based measuring systems as accurately as two kinetheodolites or two airborne measuring devices must be synchronised. It is essential for the solution of this problem to determine whether the data accuracy depends on the synchronisation error. When photographing an instrument panel in an aircraft or recording the stagnation pressure on magnetic tape, it is not useful to aim at the millisecond accuracy which is required for the synchronisation of a trajectory measuring system. Low cost equipment is then sufficient.

In all cases, reliability and protection against external interference is important for the synchronisation of complicated measuring systems. Dropouts or interference during transmission, or a short breakdown of the equipment, can hamper or even prevent a correlation of the recordings, even if one takes into consideration that most measured quantities cannot have discontinuities. All parts of the equipment must be sufficiently reliable. Not only such trivial things as adequate stabilisation of the power supply of the instruments aboard, but also the optimal installation of the aircraft antenna allowing the antenna pattern to be as favourable as possible for all sections of the trajectory and all attitudes during the tests.

11.8.1 Exact synchronisation by technical means

In the case of technical synchronisation one tries to make all measurements simultaneously. Employing measuring and recording devices which can record only at discrete times, such as cameras and incremental recorders, one tries to trigger the devices so that, taking the delays into account, simultaneous data are recorded. In the case of analog data which are continuously recorded by a strip-chart recorder or a magnetic tape recorder, the synchronisation signals can be timing marks. If a high reliability is needed, redundant time formats or redundant recording must be used as described in Section 11.5.

Advantages:

- Processing of data is relatively simple and computer running cost is low if the synchronisation equipment is reliable.

Disadvantages:

- If high accuracy is needed in technical synchronisation, the main problem is that the different measuring and recording instruments, as well as the transfer devices for the synchronisation signals, have different delays. The satisfactory control of these delays can be costly, especially when environmental factors are involved.

Exact synchronisation by technical means can be accomplished by two alternative methods: the use of several separate time bases and the use of a common time base.

Several separate time bases

A separate time standard is used for triggering each group of instruments, for instance the instrumentation on board the aircraft and the ground-based kinetheodolite system.

Advantages:

- High reliability of the synchronisation is possible. It is independent of the distance of the target to ground stations because no radio link is used during the flight.
- No difficulties with antennas on board the aircraft.
- Extremely high accuracy of the synchronisation is possible.

Disadvantages:

- Comparison of time standards before and after the flight test (see Section 11.5).
- High costs, if high accuracy and a complex time format are necessary during a long flight test.

One common time base

From a timing centre, timing signals, for instance single pulses or pulse trains are transmitted by wire or radio to the trajectory measuring and telemetry stations on the ground and to the measuring systems aboard the aircraft. It is unimportant where the centre is located. For reasons of size and weight it can be useful to install the timing centre on the ground and to combine it with a trajectory measuring or a telemetry station.

Advantages:

- Only one time standard is necessary, resulting in reduced costs and no time comparison before or after the flight test.
- Low costs of the receiving equipment for short range flight tests and for medium accuracy of the synchronisation (1 millisecond).

Disadvantages:

- A radio frequency must be available.
- A large bandwidth is necessary for high accuracy of the synchronisation.
- Difficulties with the installation of antennas aboard the aircraft.
- Unreliability caused by interference with other transmitters, unfavourable attitude of the aircraft or long distance.
- Propagation times in transmitters and receivers sometimes have to be taken into consideration.

11.8.2 Synchronisation by interpolation

The second main method, synchronisation by interpolation, dispenses with the acquisition of simultaneously measured data. On the contrary, the times at which the measured quantities are sampled during the flight test may be random. Therefore they have to be recorded to a common time scale. A kinetheodolite and several airborne cameras, for instance, run independently of each other and record the shutter return pulses of the kinetheodolite by radio and of the cameras by wire on an airborne stripchart recorder or on magnetic tape; a timing signal is recorded in the same recorder. After the test, the timing events of the different measurements are taken from the recording. Then the data are co-ordinated to a common time scale by numerical or graphic interpolation. The interpolation of data is discussed in Chapters 6 and 12 of this book. The methods of several separate time bases or a common time base as described in Section 11.8.1 can all be used.

Advantages:

- In many cases relatively cheap recorders can be used.
- No delay circuits are necessary.
- Low-cost timing equipment.

Disadvantages:

- The co-ordination of the timing events can be rather difficult and tedious, if high accuracy is required and many data must be processed. Automatic methods are possible but expensive.
- Apart from graphic methods of interpolation, the reduction to a common time scale in extended tests with several measured quantities can lead to a significant increase in the complexity of the data processing and analysis.
- When numerical interpolation methods are used, special care should be taken to eliminate first the blunder type errors. Such errors can easily occur during the reading of kinetheodolite films. In numerical interpolation a blunder error will not only affect the data in the immediate vicinity of the error, but their effect can extend over a long time interval.

This method is rather easy to apply when the time intervals between successive measurements of all parameters are equal, but the measurement times are staggered. This is, for instance, the case in time-multiplexed recordings. The interpolation becomes more complicated when the time intervals are different for different parameters and especially when the time intervals at which a single parameter is measured are not constant.

When considering the different methods of synchronisation from the point of view of the instrumentation engineer, reliability seems to be the most important aspect. The synchronisation accuracy should not be made higher than is necessary for the particular measurement considered. The method

of synchronisation should be chosen in connection with the data processing methods to be used and should be integrated in the system design at an early stage.

11.9 REFERENCES

1. Ernest H. Ehling (Editor) — Range instrumentation, Prentice-Hall, Inc., Englewood Cliffs, New Jersey, 1967.

2. F.E. Douwes Dekker, D. Lean — Take-Off and Landing Performance, AGARD Flight Test Manual Volume I, Chapter 8, Pergamon Press, Oxford, London, New York, Paris 1962.

3. L.A. Nicholls — An introduction to trajectory computation and error analysis, Weapons Research Establishment (Australia), Technical Note TRD 5, November 1959.

4. P.B.N. Nuttall-Smith, Monica J.N. Marchant — The comprehensive calibration of kinetheodolites, Royal Aircraft Establishment, Technical Report 67007, January 1967.

5. Hans D. Preuss — The determination and distribution of precise time, Ohio State University, Columbus, Ohio, Reports of the department of Geodetic Science, Report No. 70, April 1966.

6. Joseph J. Scavullo — Aerospace Ranges: Instrumentation, D. van Nostrand Company, Inc., Princeton, New Yersey 1965.

7. Th.W. Schmidt, O. Weber — Das Fehlerfeld von Ortungsanlagen, Zeitschrift für Flugwissenschaften 13 (1965), S. 15-23.

8. Merrill I. Skolnik — Introduction to radar systems, McGraw-Hill Book Company, Inc., New York 1962.

9. Merrill I. Skolnik (Editor) — Radar Handbook, McGraw-Hill Book Company, Inc., New York 1970.

10. F.O. Vonbun — Tracking systems, their mathematical models and their errors, Part I - Theory, NASA Technical Note D-1471, October 1962, Part II - Least squares treatment, NASA Technical Note D-3776, December 1966.

11. O. Weber, A. Wallenhauer — Die Flugbahnmeßanlagen der DFL - Ausbau, Einsatz und Vergleich, DFL-Bericht Nr. 169 der Deutschen Forschungsanstalt für Luft- und Raumfahrt, Braunschweig 1961, 266 Seiten, 100 Bild., 26 Lit.

12. O. Weber

Untersuchungen über die systematischen und zufälligen Fehler bei Start- und Landemessungen mit einem einzelnen Kinotheodolit,
Deutsche Luft- und Raumfart, Forschungsbericht 67-55,
Juli 1967, 80 Seiten, 28 Bild., 4 Tab., 12 Lit.
(Investigations on the systematic and random errors arising in the measurements of take-off and landing of an aircraft with a single kinetheodolite, by O. Weber,
Royal Aircraft Establishment, Library Translation No. 1317,
September 1968)

CHAPTER 12
DATA PROCESSING

by

J. Perrochon and J.T.M. van Doorn

12.1 INTRODUCTION

The use of recording methods which provide data in electrically retrievable form and of digital computers for the processing of these data has had a large impact on flight testing. The number of parameters which can be handled has increased tremendously; it would be impossible to process by manual methods the 1000 or more parameters that are measured by some of the modern flight test data collection systems. More complex operations can be applied to each parameter or group of parameters. The combination of more parameters and a more detailed analysis make it possible to provide much more information than was possible without the use of computers and is the basis of many advanced flight test methods mentioned in Chapter 1.

The planning of the processing by computers requires much effort. During manual data processing the engineer sees the results of each step and will more or less automatically detect errors that may have crept in. Without a conscious effort he will locate blunder errors, smooth data, find out that wrong equations have been applied because the results cannot be true, etc. When the data have been processed by a computer the engineer only sees the final results, from which it generally is much more difficult to detect whether errors have been made on the way. Therefore, various kinds of tests and rejection criteria have to be incorporated in the computer program. Because of the larger amount of information obtained from the data, the computer analysis must be extended further than is usually done in a manual analysis in order to reduce the amount of (manual) work involved in interpretation. Computer processing has developed into a specialized science and these specialists, unlike the engineers who do the manual processing, often do not understand the specific objectives of the flight tests. A very close co-operation with the flight test engineers is, therefore, essential both during the original setting-up of the program and when modifications or extensions are required.

It is not even possible to divide the system into an airborne data collection system designed by instrumentation engineers and a data processing system designed by data processing specialists. The tasks of each sub-system change as technology improves. For instance, digitizing formerly was a data processing operation done on the ground from analog recordings; now digitizing is usually done in the aircraft as part of the data collection system. Airborne computers are used more and more and they execute many of the operations which were previously done in the data processing ground station.

In this book on flight test instrumentation it will not be possible to give a detailed treatment of all data processing methods. This last chapter will highlight those aspects of data processing which are of interest to the flight test and instrumentation engineers in their design work. It is mainly a functional analysis of data processing. Software and hardware techniques will only be discussed in so far as they are necessary for a clear understanding of the problems of the overall design of a flight test instrumentation system.

12.2 FUNCTIONAL ANALYSIS OF DATA PROCESSING

12.2.1 General aspects

The main functional divisions of data processing operations presented in Chapter 2 are:

- instrumentation checks and quick-look processing
- preprocessing
- computation
- data presentation.

These topics are discussed separately in the following sections. The discussion is preceded by a review of the types of input, and followed by a section on validation and interpretation. In Section 12.3 some data processing techniques are analysed in more detail and in Section 12.4 a more detailed discussion is given of some of the equipment used.

12.2.2 Types of data input

A flight test data centre receives several types of information:
- data measured in the aircraft or ground-based installations
- information from the flight test engineer on the required amount and kind of data to be processed
- information from the instrumentation department on the configuration of the recording system and on the calibrations which have to be applied to each parameter.

The recorded data can be of many types. The most important are:
- photo-panel data
- continuous-trace recordings
- analog magnetic tapes which may carry continuously recorded and/or sampled data, using one or more modulation techniques such as AM, PDM, FM (see Chapter 9)
- digital magnetic tapes with parallel or serial recordings in several different codes
- "pre-detection" recorded telemetry data (i.e. still modulated on a carrier frequency or at least before separation of the sub-carriers)
- data from ground-based installations such as kinetheodolites.

The recording format must be defined well before the start of the flight tests, so that the preprocessing equipment can be prepared. The information required includes the code or modulation method, the number of channels, possible subcommutation or supercommutation lay-outs, etc.

The information from the flight test engineer must indicate:
- which parameters have to be processed and what operations have to be done on these parameters
- which parts of the recorded data have to be processed.

The first is usually sent to the data processing centre some time before the flight, so that the data processing personnel can make preparations to begin data processing as soon as the data recordings arrive. As the decision on the type of flight test to be executed may depend on considerations such as weather conditions and availability of equipment, this information cannot be expected at a very early stage. The data processing software and the storage of other data such as calibrations must, therefore, be designed in such a way that the programs and calibrations required for each type of test can be made available quickly. The decisions on which portions of the recorded data are to be processed can only be made after the flight has been completed. It will include conclusions drawn by the pilots and by observers who were on board during the flight or followed the flight progress from on-line telemetered data, and often requires inputs from a quick-look run on a preprocessing computer.

The information from the instrumentation department should include the following items:
- the recording channel on which each parameter can be found
- the calibrations of each channel.

This information usually becomes available only after the aircraft has taken off, because of the possibility of last-minute changes during the instrumentation checkout just before the flight. In some cases even in-flight changes may be made in the instrumentation. The calibration data are usually given in two stages:
- a listing of the components used in measuring each parameter
- the calibration data for each component.

As a late delivery of the calibration data can have a strong influence on the turnaround time of the data processing, a rather sophisticated administration system is required. Some aspects of this are discussed in Section 12.2.4 and in Chapter 7.

A closely related problem is the long-term storage of data. For some types of flight tests, such as investigations of ad-hoc problems in operational aircraft, the raw data can be destroyed when the data processing and interpretation is finished. Only the essential processed test results are retained in a test report. But most flight test data have to be stored for longer periods, especially those from prototype flight tests and tests with experimental aircraft. When unexpected characteristics of the aircraft or its systems are found, it is usually less costly to look for corroborative evidence in the data of previous flights than to make a series of new flights. When the non-

steady flight test techniques mentioned in Chapter 1 are used, the availability of earlier flight test data is even an essential characteristic of the data analysis procedure. Many manufacturers keep their flight test data as long as aircraft of that type are flying; they can often be of great assistance when a solution has to be found for problems that only become apparent after the aircraft are in operation. The data which are kept are always the original flight data, because they contain the maximum amount of information.

12.2.3 Quick look and instrumentation checking

These two operations must be done as quickly as possible after the flight, before the main data processing is started. They have many requirements in common and are sometimes regarded as a single operation even though they are needed by different people. The quick-look data provides the flight test engineer the information needed to determine whether the test objectives have been met and what parts of the flight data are most suitable for final processing. He uses this information to decide on the final data processing instructions for the data from the flight which has just ended and to plan the next flight. The instrumentation check data are used by the instrumentation engineer to identify any failures or deteriorations in the data collection system which must be repaired before the next flight can start.

The quick-look information can usually be obtained from the analysis of a few parameters. It can be obtained on-line or off-line.

On-line quick-look information can be obtained from:

- on-board observers who follow the time history of the essential parameters on an instrument panel or on a continuous-trace recorder which shows the traces immediately
- telemetry of the essential parameters to the ground, where they can be displayed in real time.

If the essential parameters have to be calculated from the measured data, additional computation can be done either by an on-board computer or on the ground before display. Essential real-time information can also be obtained from radio reports by the pilot.

Off-line quick-look information is obtained from a preliminary postflight analysis of the essential parameters recorded during the flight. This is relatively easy to do from continuous-trace recordings, which can be examined immediately or after photographic development. Quick-look analysis from magnetic recordings requires more sophisticated equipment, especially for digital data (see Section 12.4.2).

Quick-look data can often also be used for checking the functioning of the instrumentation: a failure or partial failure will become immediately apparent from the analysis. If all data are recorded on continuous-trace recorders, the instrumentation check and the quick-look information can usually be obtained simultaneously when the flight test engineer (who knows how the aircraft should have flown) and the instrumentation engineer (who knows how the instruments should react) examine the recordings together. For multi-parameter systems recording on magnetic tape the quick-look analysis will usually only provide evidence on a small number of data channels. Although this provides some very important information (that the system has been switched on, that the tape recorder has functioned properly, that the quick-look channels have performed properly, etc.), failures in other channels are still possible. The instrumentation engineer also needs more detailed information. If a failure has occurred, he must know what part of the equipment has failed. This additional information is obtained from three sources:

- preflight and postflight checks of the equipment
- self-test and self-calibration functions supplied by test equipment incorporated in the data collection system
- an (computer) analysis of the data.

The first two sources are discussed in more detail in Chapter 8. If computer processing is necessary, it is usually incorporated in the preprocessing phase.

12.2.4 Preprocessing

The division of data processing, or at least of automatic data processing, into two parts, namely, preprocessing and computation is generally accepted. There is, however, less agreement on the division of the different processes between these two parts. This is mainly because the division

is usually made from the hardware point of view. The data collection subsystem of an automat. flight test instrumentation system usually provides the data on magnetic tape in analog form or in a digital format which cannot be fed directly into a general purpose digital computer (see Chapter 8). The data processing equipment then usually consists of two parts: the preprocessing equipment which has as its main function the conversion from analog to digital and the conversion of digital data to the standard computer format, and a general purpose digital computer. The division of the different data processing tasks between these two systems depends on many considerations such as speed and memory capacity of each of the two systems and availability of the general purpose digital computer. These can differ considerably for different installations. In this chapter the division is made from a more functional point of view: "preprocessing" will include all processing operations which are applied to each recorded channel individually in the same sequence as the information was recorded; "computation" will be used for operations which involve the combination of information from more than one channel and for operations on one channel which do not follow the original time sequence (such as frequency analysis and statistical operations). This division, which in general conforms with the functions of the preprocessing and computation hardware systems (though, as said before, notable exceptions occur) has one other convenient aspect. The preprocessing functions either require direct inputs from the instrumentation engineers (as the application of calibrations) or are related to their work in the design of the data collection system (as channel selection and filtering). The computation functions have no direct relation to the data collection system; they are mathematical operations applied in order to accelerate and simplify the interpretation of the test results.

In non-automatic data processing the processing functions are roughly similar to those in automatic processing, though differences occur due to the fact that the operations are performed by human operators. The computation operations in non-automatic processes are usually small or even non-existent. Sometimes transitions between non-automatic and automatic processing occur in the preprocessing phase. For instance, continuous-trace recordings can be manually converted to discrete digital readings and then further processed in the automatic systems.
The discussion on preprocessing and computation will be mainly concerned with automatic processing, but occasional remarks will be made about aspects of non-automatic processing.

The main preprocessing functions are:
- copying of the original data recordings
- selection of the parts that must be processed
- selection of the channels that must be processed
- analog-to-digital conversion
- elimination of blunder errors
- filtering and smoothing
- reduction of the number of data points in each channel
- application of calibrations
- time correlation between channels
- production of computer-compatible tapes.

These functions will be briefly characterized below, in Section 12.3 a few of these functions will be discussed in some more detail. It must be stressed here that these functions are not always executed in the sequence given above and that, as stated before, they are not always executed by the preprocessing equipment. Filtering and smoothing, and the application of calibrations, for instance, are often part of the processing in a general purpose computer. But as they functionally belong to the preprocessing as defined above, they will be mentioned here.

The first preprocessing operation usually is the copying of the original data recordings. It is extremely important to ensure that the valuable information can under no circumstances be destroyed or lost. Magnetic tapes are often copied immediately after they enter the data processing centre and the original tapes are stored in archives (see also Section 12.2.2). All further operations are then done with the copy. For continuous-trace recordings the parts which are to be further processed are often copied; then the original recordings cannot be damaged and will be available later.

It is usually not necessary to process all the data that have been recorded. An important part of the preprocessing is, therefore, the selection of the parts that must be processed. This selection

can be made during the quick-look processing mentioned in Section 12.2.3. For both purposes it is necessary to examine a few channels on which the main parameters for the test have been recorded. As often more channels have been recorded than are of interest for a particular test, the next step is to select the channels which must be processed. A careful execution of these two operations can significantly reduce the quantity of data which must be processed and thereby reduce the time and the cost involved in the data processing.

Analog recordings will either be processed by analog computation methods (see Section 12.2.5) or will be converted to digital form. For the analog-to-digital conversion of analog recordings on magnetic tape most computers have standard peripheral equipment, which usually will require a special interface unit for demodulation of the signal. Analog recordings from continuous-trace recorders, photo-panel recorders and kinetheodolites cannot be digitized by automatic methods. There is, however, semi-automatic equipment which can considerably speed up the digitizing of such recordings (see Section 12.4.1).

The operations which now follow must be applied to each channel individually. They are intended to convert the data into such a form that they can be more easily processed. The first step must be to remove the blunder errors. If these are left in, serious difficulties in the final interpretation can occur, especially since the influence of these errors is obscured in the final results. Several types of blunders can occur. Some can be due to bad contacts in the data collection system, others can be errors of one bit in a digital word due to a bad spot on the tape. They can be detected by putting limits on the jumps that can be allowed to occur between successive measurements of the same parameter. This process is often combined with smoothing, i.e. the elimination of random errors in the individual measurements. Computer smoothing is often done by determining the best polynomial through a number of data points by least-square methods. It is very important that the blunder errors are removed before the actual smoothing process is executed; a single outlying blunder error can cause large errors in the final smoothed curve. Though most filtering is done in the data collection system, at least in sampled systems, it may be necessary to do some additional filtering in the ground station. Filtering also plays an important part in the interpolation and reconstruction of sampled data (see Chapter 6). In some cases channels have been sampled much more than is actually necessary for final processing. For those channels a reduction of the sampling rate can be made to reduce the work to be done. This reduction of the sampling rate should always be done after all smoothing and filtering operations have been finished. A brief discussion of smoothing and filtering is given in Section 12.3.2.

The most important operation on each individual channel is the application of the calibrations, which converts the data to engineering units. A general discussion of calibration is given in Chapter 7, details of the methods of applying the calibrations during data processing are given in Section 12.3.1.

If the time difference between events in different parameters must be exactly known, time correlation may be necessary. The relative timing of the value in two channels may be shifted in the recordings because:

- different lags or phase shifts occurred in the measuring channels of the two parameters
- the two parameters were sampled at different times
- the two channels were recorded in different recorders, these may then have had different time bases.

The methods used for establishing time correlation are discussed in Section 12.3.3.

The final operation in preprocessing usually is the conversion to a computer-compatible tape which can be read by a general purpose computer. As the data at this stage usually are already digitized, a digital format conversion is usually required which can include one or more of the following operations:

- conversion from serial to parallel
- change of the number of tracks of a parallel recording
- digital code conversion
- arranging the data in standard-length blocks, separated by inter-record gaps.

As already stated, the preprocessing functions mentioned above do not always coincide with the actual operations done in a preprocessing equipment: in many data processing stations some of the preprocessing functions (such as digital filtering, application of calibrations) are done in the general purpose computer, but it is also possible that some of the simpler computation functions (such as the calculation of Mach number from static and total pressure) are done in a preprocessing computer. The conversion to computer-compatible tape, though functionally the last step in preprocessing, is sometimes done at the very beginning to facilitate the other operations that have to be performed by the preprocessing computer. The hardware considerations of the preprocessing station are discussed in some more detail in Section 12.4.3.

12.2.5 Computation

The computation functions in data processing are aimed at transforming the corrected time histories supplied by the preprocessing into quantities which are more readily adapted to interpretation. They may involve very simple operations such as the determination of a minimum value of a certain parameter or very complicated operations such as the determination of stability derivatives from simultaneous partial differential equations, or the statistical analysis or frequency analysis of a number of parameters. Often computation is not necessary at all: if all required information can be read directly from the time history, data processing does not go beyond the preprocessing stage.

Computation can be done by hand, by analog computing devices or digital computers. Computation by hand is still the most universal method because the computation can be adapted to the interpretation which goes on simultaneously. Such things as the determination of the maximum value of a noise signal, or the analysis of a pulse waveform in an electronic device, are very easily done manually. Automatic methods are used only if the quantity of data is very large, or if too much calculation is involved. Automatic computation can be done by analog or digital computers. Analog computers are very useful in on-line computation processing because they often are faster than their digital counterparts. They also have advantages in some computations involving models, and in some fields of computation such as frequency analysis. Most of the automatic computing is, however, done on digital computers. These are especially suited for performing large numbers of relatively simple computations (which often occur in flight test analysis), especially if high accuracy is required. Digital computers are often easier to program and they can have large memories in which data or administrative information can be stored. As the speed of digital computers increases, they take over many of the fields which were previously reserved for analog computation, especially in the field of frequency analysis and computations involving models. For some tasks hybrid computation systems, involving both analog and digital computers connected by analog-to-digital and digital-to-analog converters, are used.

The computation stage requires a very careful planning. A computer can very easily produce a large mass of numbers, which will require enormous manual labour when they have to be interpreted. The planning should be done in three stages:

- the computations should be carefully prepared to ensure that indeed the objectives of the flight tests can be derived from the results
- the quantities which must be presented for interpretation and their form of presentation should be selected. Too much information will hamper the interpretation; overlooking, however, a single parameter may result in a costly rerun of the computer
- the method by which the quantities will be calculated should then be chosen in accordance with the characteristics and the capacity of the available computer. If this method and the corresponding computer programs have not been carefully planned, the required memory space and calculation time can become too large.

The planning should be done at a very early stage, as it may cause additional requirements for the parameters to be measured and for the preprocessing work to be done before the data are entered into the processing computer. Ample time must be allowed for the actual programming and for the testing of the programs. If possible the programs should be tested using suitable simulated inputs. During the actual programming a close contact between the programmer and the flight test engineer should be maintained.

12.2.6 Presentation

The presentation of the results of the computations can be in tables or on graphs. Tables are the easiest format for the computer engineer. They can be produced by standard peripheral units. Automatic typewriters can be used if the output rate is low. With line printers much higher output speeds can be obtained: for example 1000 lines per minute, each line consisting of 130 figures. An additional advantage of tables is, that the full accuracy of the results can be retained. From the point of view of the engineer who has to do the interpretation, graphs are often easier to use. The automatic plotters which are normally used with digital computers are much slower than the line printers, and require careful planning of the scale values if sufficient accuracy is to be retained. Electrostatic mosaic printer/plotters, which are coming into general use now, are much faster. They require digital inputs and can be accurate to 0.1 % or better, and can also print characters. An interesting method of presentation is provided by interactive computer graphic display systems. The observer can operate the computer; the results of these operations are immediately displayed. The computer results can thus be modified before the final graph or table is produced.

The lay-out of the tables and figures should be programmed in such a way that they can be directly published in test reports.

12.2.7 Validation and interpretation

The task of the data processing department is not completed when the computer has produced an impressive amount of tables and/or graphs. Before delivering these to the flight test engineers, the data processing department should check all output data for errors and should determine whether the requested accuracy has been achieved. This process of validation of the applied computer operations is, however, often neglected. If this occurs, then this work has to be done by the flight test engineers who are often less well prepared for understanding what could have gone wrong in computer processing.

The interpretation can, in fact, be considered to be a continuation of the validation. The flight test engineer usually knows (from theoretical or simulation studies) what to expect from the test. Ideally, the test results will validate the theoretical models which were used. If the results differ from the predictions, either the physical phenomenon investigated was different from what it was thought to be, or there has been some error in the measurements or in the data processing. Then the theoretical background of the predictions should be reconsidered, and the test and data processing procedures should be checked until the discrepancy has been found. The investigation of unexpected results is often more difficult if automatic data collection and processing systems have been used. During manual processing the human operator consciously follows every step in the data processing and will often find that something unpredicted has occured long before the final result has been calculated. In automatic systems the human interpreter often only sees the final results. It may be necessary to repeat the processing and to have outputs at intermediate stages before the reason for an unexpected result can be found.

Even if after interpretation the operation has been judged to be satisfactory, one final step should be taken before the results are published in a test report. This is what has been called the "meditation about the true value" of the results in the analysis of the process of measurement (Chapter 3, Section 3.2, phase 5). The flight test engineer should reconsider whether the test results really provide a relevant answer to the problems for which the test was conducted. It is better to point out in the conclusions of the test report any remaining uncertainties than to have them discovered later by others.

12.3 SHORT DESCRIPTION OF A FEW PROCESSING TECHNIQUES

12.3.1 Application of calibrations

The calibrations are used to convert the measured data from the units in which it was recorded (for instance, millimeters on a continuous-trace recording or numbers from 0 to 1023 in a ten bit digital recording) into the engineering units in which they must be interpreted. The principles of calibration from the point of view of the instrumentation engineer have been described in Chapter 7. Here only the data processing aspects will be briefly summarized.

When setting up the sequence of preprocessing operations it should be kept in mind that, in principle, it is necessary to apply the calibrations before smoothing operations are performed. If the calibration is very non-linear, smoothing before the application of the calibrations will not provide the best curve through the data points. This is especially true if the calibration shows kinks, as for instance for airspeed indicators which have been linearized in airspeed by a number of springs. In practice it is often more convenient to first reduce the number of points by smoothing, so that the calibrations are applied only to the points which will be further processed. If this procedure is applied, it should first be checked whether the resulting errors can be neglected.

In Chapter 7 it has been mentioned that the overall calibration of a measuring channel is usually determined from the individual calibrations of several components. The combination of these component calibrations must be done with care and on the basis of a good understanding of the characteristics of each component. The number of calibration points must be carefully chosen by the calibration engineer, in relation to the required accuracy.

When preparing the calibration data for application during data processing, individual channels may have special requirements due to the following reasons:

- the instrument has hysteresis
- in-flight calibration points have to be taken into account
- the final calibration may depend on a variable which is measured in another channel. Such variables may be the supply voltage, temperature or a parameter which causes cross-axis errors
- the parameter is measured by a coarse-fine method on two channels.

These aspects will be separately discussed below.

In case of hysteresis the calibration will usually be made first by increasing the input parameter slowly to the desired values and then decreasing it in the same way. The same values of the input parameter will be used during the increasing and the decreasing part of the calibration, though often not all values are taken during the decreasing part (see Fig. 12.1). The final calibration usually is determined by the average of the "increasing" and "decreasing" values of the input parameter. The points where no decreasing values have been taken are interpolated. Usually the average calibration so obtained is sufficiently accurate. Only in cases where extreme accuracy has to be obtained, will it be necessary to use special calibration data which have been measured during a simulation of the expected flight conditions (see Section 7.4).

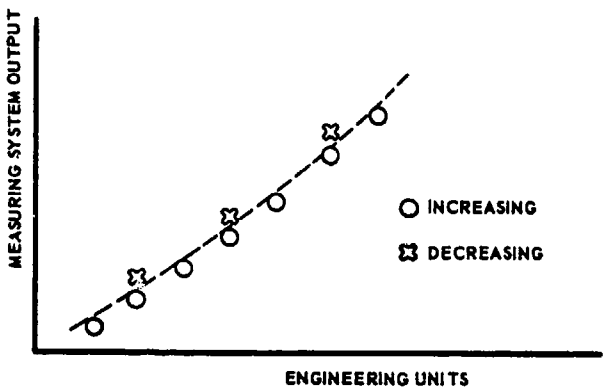


Figure 12.1 Example of a calibration curve showing hysteresis

In some instrumentation systems in-flight calibration points are taken. Usually these are used to verify whether the calibration has changed and do not affect the calibration values to be applied during data processing. Sometimes they are, however, used to adjust the zero points and/or the sensitivity of the original calibration. If that is necessary, the computer program for the application of the calibrations should be adapted to make these corrections.

If the calibration depends on a value measured in another channel (supply voltage, temperature or a cross-coupling parameter) the value of this other parameter must be determined before the calibration is applied. This will usually mean that the calibration of this other parameter has to be applied first. When the other parameter is the supply voltage or temperature, a constant value can often be used for part of the flight or even for a complete flight. For effects such as cross-coupling, the calibration must be adjusted at each point.

In some cases where the accuracy obtainable by a single channel is not sufficient, a parameter is recorded on two channels, a coarse and a fine channel. (see Fig. 12.2). The coarse channel, which is single-valued for the complete range, is only used to determine which of the fine-channel calibration curves has to be used.

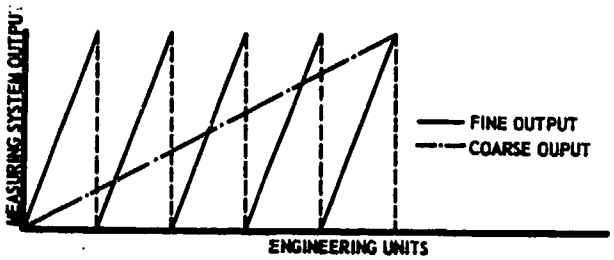


Figure 12.2 Calibration curve of a coarse-fine system

A calibration can be stored in the computer by two methods:
- the "polynomial method"
- the "table method".

Using the polynomial method the calibration curve is approximated by a polynomial function. The advantage of this method is, that only the coefficients of the polynomial have to be stored in the computer memory, which requires very little memory space. The coefficients of the polynomial can be determined in a separate computer program which calculates the polynomial of the lowest degree which fits the calibration points within specified limits. The degree of the polynomial should not be made too high, because there can then be anomalies between the calibration points. Usually most calibrations can be approximated sufficiently by a third-degree polynomial, in exceptional cases up to fifth-degree polynomials are used. If extreme non-linearities occur (as for instance in the lower range of normal pointer-type airspeed indicators) it may be necessary to use two or more intersecting polynomials. In any case it will be necessary to display the calibration curve, together with the calibration points, to the calibration engineer before it is approved for data processing. It does happen that the curve chosen by the computer program, though it fits the points within the required limits, does not represent the calibration sufficiently well in the regions between the points. In any case extrapolation should not be allowed (see Fig. 12.3).

When the table method is used, the complete table of calibration points is stored in the memory of the computer. Generally, linear interpolation is used to determine the values between these points. This method requires more memory space and the actual computation may also take more time than with the polynomial method.

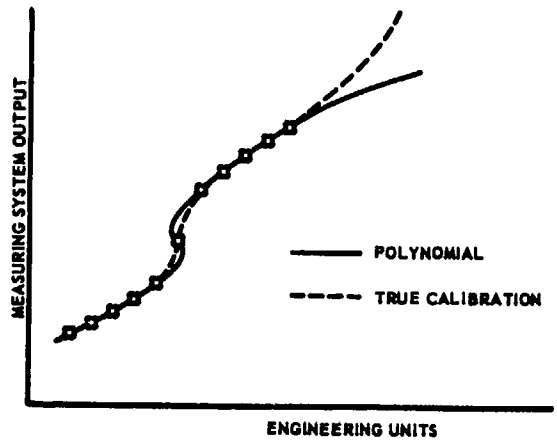


Figure 12.3 Examples of errors that can occur by interpolation and extrapolation using the polynomial method

A careful check of the calibration must be made by the calibration engineer before it is released for use in data processing. Whenever possible this check should include the calibration data that are entered into the computer as well as the form in which the application programs will use them, as discussed in Chapter 7.

If a calibration has been made during the postflight check (which may be necessary if a component has been replaced just prior to the flight), it may take too much time to have the calibration carefully checked by a calibration engineer before it is used for data processing. If the polynomial method is used, the time delay must simply be accepted. The advantage of the table method is that it is very improbable that a wrong calibration will be applied if the calibration data have been carefully checked during the actual execution of the calibration and if the transcription has been checked for writing or punching errors. If at all possible, the normal check should, however, also be made when the table method is being used.

12.3.2 Smoothing and filtering

As already stated in Section 12.2.4, the word "smoothing" is used for reducing random fluctuations in the measurements, while filtering denotes modification of the frequency spectrum. These two concepts are, however, closely related and smoothing can be done by means of a low-pass filter. The cut-off frequency of the filter should be below the sampling rate of the signals to be smoothed, but well above the frequencies of interest, because otherwise errors of omission (as defined in Chapter 6) will occur in the result. Both analog and digital filters can be used. Smoothing and filtering are especially important if the data processing involves differentiation.

The functioning of filters has been discussed in Chapters 3, 5 and 6 of this book. For sampled data the discussions in Chapter 6 are of great importance. Frequencies higher than half the sampling frequency introduce aliasing errors. These cause spurious signals at lower frequencies which cannot be eliminated. The sampling frequency in the data collection system should, therefore, be chosen with care and additional pre-sampling filters should be applied in the data collection system where necessary. Aliasing errors can, however, also be introduced during data processing if the data rate from a channel is reduced before filtering is applied.

Digital filters have, as analog filters, an amplitude and a phase characteristic and the filters should be chosen so that the errors of omission and the errors of commission defined in Chapter 6 do not become significant. Digital filters are based on convolution, either by means of time domain algorithms or by means of the Fast Fourier Transform. Implementation can be done with special-purpose hardware or in software for general-purpose computers. The advantages of digital processing are the flexibility and the very accurate and drift-free operation, although quantization effects in both signal and coefficients must be taken into account. There are also adaptive filtering methods, in which the filter characteristics are automatically adapted to the frequency of the low-frequency part of the signal (see References 1, 2 and 3).

12.3.3 Time correlation

Time correlation is required when the values of two parameters must be determined at the same time or when relative phases of two parameters must be determined. As in each individual measuring channel a lag or phase shift can occur, it is necessary to reconstruct the original curveform from available data on the dynamic characteristics (see Chapter 3) before time correlation can be established. In practice two types of time correlation can be distinguished:

- the signals have been recorded by the same recorder or by different recorders with the same time base. If the signals have been recorded continuously the measurements in both channels can simply be read at the same time. If the signals have been sampled, one of the signals has to be interpolated at the time at which the other was sampled as described in Chapter 6.
- the signals have been recorded by different recorders which do not have the same time base. This often occurs when one recorder has been used on the ground (for instance with a kinetheodolite system) and the other has been used for making measurements in the aircraft at the same time. In that case a third time base will sometimes be used, which can be recorded simultaneously in both recorders, for instance by means of a radio link or by having two sufficiently accurate clocks recording on both recorders. This latter case is discussed in detail in Chapter 11.

Linear or higher-order interpolation can be used as described in Chapter 6. In general the frequency of the common time base can be less if higher-order interpolation are used for obtaining the same accuracy. The computations are, however, more time consuming.

When data from different recorders have to be synchronized, it is often difficult to find out which time base pulses on the one recording can be correlated with those on the other recording. In the past, this has often led to severe problems. One solution is to use coded time base signals, so that the correlation can be established by reading the code. There are, however, several other methods for establishing the initial time correlation, such as starting the recorders at the same time and counting the number of pulses generated by the common time base. If the normal correlation has failed, it is often possible to restore it by finding particular events, such as conspicuous manoeuvres of the aircraft, on both recordings and to start counting pulses from there (see Chapter 11).

12.4 SHORT DISCUSSION OF DATA PROCESSING EQUIPMENT

12.4.1 Equipment for analyzing photo-panel recordings and continuous-trace recordings

The reading of photo-panel recordings is a purely manual process. The film frames are projected one by one and the relevant instrument dials have to be read in a predetermined sequence. Channel selection is possible, i.e., the operator only reads the instruments which are necessary for a particular analysis. The data read from the film can be collected in tables or can be punched in paper tape for further analysis in a computer. It is possible to read about 500 data points per hour.

Many attempts have been made to automate the reading of continuous-trace recordings, but without much success. Semi-automatic equipment is now generally used which provides a desk with a film transport mechanism, on which the film can be laid or projected. The operator can move cross hairs to the point to be measured. When the cross hairs coincide with the point, the operator pushes a button and the co-ordinates of the point are automatically recorded on paper or magnetic tape. These devices make it possible to read 1000 to 2000 points per hour.

Similar devices are also used for reading photo-theodolite films (see Chapter 11).

12.4.2 Equipment for quick look and instrumentation checking

The task of this type of equipment is discussed in Section 12.2.3 and can be briefly summarized by saying that generally for quick look a rough trace of a few channels is necessary; for instrumentation checking it is necessary to verify whether all channels have produced outputs which vary within predetermined limits and whether the calibrations have not changed. As described in Chapter 8, a number of these instrumentation check requirements can be fulfilled by counters and warning lights in the aircraft and by preflight and postflight checks which can be recorded on the same tape as the data. In some cases in-flight calibration data have also been recorded on the tape.

In general the equipment for quick look and instrumentation checking is used to extract a small part of the information recorded on the tape and display it to specialists. For this purpose the raw data are often considered to be sufficient and no calibrations, filtering or computation have to be applied. For quick look a graphical presentation is often preferable, for instrumentation checking tables are usually easier to handle.

In most cases the preprocessing equipment is used for obtaining quick look and instrumentation check data. It is usually done in a preliminary run of the tape through the equipment and is often combined with the selection of parts of the tape that must be further processed.

Special problems occur when the flight testing and the data processing are performed at different locations. Then, sometimes, special transportable equipment is used for quick look and instrumentation checking, often mounted in a van. The equipment will generally be built along the same lines as the preprocessing equipment and will often use the same components. As this is a costly procedure, continuous-trace recorders which only record the quick look parameters are sometimes mounted in the aircraft. The cheking of the normal instrumentation must then be done by other means.

12.4.3 Preprocessing equipment for magnetic tape inputs

The equipment of a preprocessing ground station must be able to handle magnetic tapes which may vary in the following aspects:

Tape width and track arrangement. Tape widths from 1/8 in. and 1/4 in. (in commercially available cassettes) to 2 in. are in use in both airborne and ground equipment. Flight test standards have been made by IRIG (Ref. 4) for 1/2 in. tape with 7 or 9 tracks and for 1 in. tape with 14, 16 or 31 tracks. Most tape recorders specially manufactured for airborne applications are constructed according to these standards.

Modulation methods for analog recording. The signals are recorded on tape by direct recording, PDM or FM. Several types of FM recording are in use (see also Chapter 9). IRIG has only tape recording standards for single-carrier FM for several combinations of carrier frequency and tape speed. The multi-subcarrier systems standardized for telemetry are also used for tape recording. These include both proportional-bandwidth and constant-bandwidth systems.

Modulation methods for digital recording. Digital tapes can be recorded in parallel or in series by several modulation methods (e.g. NRZ or bi-phase). Parallel recordings can have different numbers of bits per character. Serial recordings can have different word and frame synchronization methods. The detection of words and frames can be done either by hardware or by software. The hardware methods are normally faster, software methods are more flexible.

Different types of telemetry tapes. These may be recorded in the telemetry ground station with a carrier (predetection recording) or after detection (postdetection recording). In analog and digital telemetry most of the modulation methods mentioned for analog and digital flight tapes may occur, though sometimes in other variations than are used for flight tapes by the same flight test centre.

Important design characteristics of the preprocessing station are:

- the degree of versatility. Will the centre have specialized preprocessing equipment for each of the variants mentioned above, or should all types be handled by one versatile piece of equipment? Although there is a general tendency towards less specialization in this respect, it has in some cases been found that significant delays can occur because the preprocessing equipment is engaged in time-consuming processing of other inputs.
- the degree of automation. In early quick-look and preprocessing computer systems it has been found that the manual preparation of these systems and manual test procedures and fault detection require considerable time. In modern systems a high degree of automation of these functions is normally specified.

In most modern flight test data processing stations separate "preprocessing" and "computation" computers are used. The main reason for this is, that many of the preprocessing functions (such as copying of flight tapes, channel selection, data reduction within each channel, digital format conversion and the production of computer compatible tapes) require relatively long computer input/output (I/O) time but only very little computation time. As small computers with the same I/O speed as the large computers have become relatively inexpensive, the best cost effectiveness is obtained if these functions are done by such small computers. The large computers, which are often used for many purposes other than flight test data processing, are then more efficiently utilized. The division of the preprocessing functions between the two computers depends on many considerations, such as the availability of the large computer, the turnaround time required, etc. In some cases all preprocessing functions mentioned in Section 12.2.4 are executed in a preprocessing computer, if necessary in several consecutive runs. In other cases the more complex preprocessing functions, such as filtering and the application of calibrations, are done in the large computer.

As the flight tapes usually do not have inter-record gaps, the input tape unit to the preprocessing computer has to run continuously. This means that the preprocessing computer functions in an "on-line" mode even if further processing is not on line. The problems mentioned for on-line operation in Section 12.4.4, therefore, always apply to preprocessing computers. This on-line operation need not, however, be done at the same speed as the data were recorded, it is possible to read the tapes at a higher or lower speed than they were recorded.

12.4.4 Computers

When selecting a computer system, the first choice is between an analog and a digital computer. Few, if any, data processing stations are without a digital computer at the present time. But often there are, besides this digital computer, some analog computing devices which may be either standard analog computers or special-purpose devices such as frequency analysers, etc. The main advantage of analog computers is their inherent speed. For this reason they can sometimes be used in on-line operations for which the available digital computers are not suitable. Examples are frequency analysis and computations with models which have non-linearities. As the speed and capacity of digital computers increase, these advantages become less and less apparent. The present trend is towards the replacement of analog devices by digital computers.

The choice of the digital computer depends heavily on the amount and the kind of work which must be done and on the required turnaround time. For computations involving a small amount of data a desk computer or a terminal to a large general purpose computer system may be sufficient. For more demanding

flight test programs a general purpose computer may be shared with others or even one or more computers may have to be reserved for this purpose. The main aspects to be considered in the choice of a computer are:

- The hardware system. Even if a preprocessing computer is used for data reduction, the number of I/O operations of the computer usually is larger for data processing than for many other computer applications. Modern computers can have separate processors for peripherals such as tape-units, discs, drums, card readers, printers, etc., which can operate simultaneously with the central processing unit.
- The memory cycle time. This gives a general indication of the speed of the computer.
- Multi-programming. Because of the large number of relatively slow I/O operations required in flight test data processing, the central processor of the computer is rather inefficiently utilized. This can be improved if the computer has multiprogramming capability. In such computers several programs are stored in the memory and the computer will start working on the program with the highest priority until an input or output has to be done for that program. Then the computer will switch to the program with second priority while a separate controller takes care of the input or output for the first program. When this has finished, the computer will switch back to the first program while an I/O controller takes care of the input and output for the second program, etc. If the number of simultaneous programs is small, this can considerably improve the efficiency of the computer. If the number of simultaneous programs becomes too large, excessive memory capacity and too long a turnaround time for the low-priority programs will defeat the purpose.
- On-line processing. Until recently, this technique was mainly used for a small number of channels which were watched continuously during flight on oscilloscope displays, often only during dangerous flight tests, such as flutter tests. In the most recent flight test systems (Ref. 4 and 5 of Chapter 1) on-line processing is used to a larger extent. The main problem from the point of view of computer technique is, that the processing must on the average be as fast as the input data come in. This gives additional requirements on the programming of the data processing, and in some cases it may be necessary to do the programming in computer language because this will decrease the program execution time.
- The operating system. This is the total of all software programs which executes and monitors the computer operations. It includes programs for management and arrangement of data streams, the drivers for the various peripherals, programs for protection, testing and intervention. It performs all functions that a programmer will use in his application program.
- Compilers. Different programming languages can be used for programs such as on-line programs, programs with much I/O, programs for certain complicated numerical calculations, etc. The compilers for these languages are not available for all types of computers.
- Compatibility. There are several compatibility problems which can influence the choice of a computer system. In the first place it has been noted that a "computer compatible" tape produced by one computer (for instance a preprocessing computer) often cannot be read by other computers because of the extremely narrow tolerances in tape readers. Also, there may be differences in compilers, even if they have been made nominally for the same computer language. This may require extensive and often difficult rewriting of already existing and proven programs.
- Access to the computer system. If the same computer is also used for other applications, the priority assigned to the flight test processing programs may heavily influence the turnaround time.
- Possibility of human intervention. Though many imperfections in the test data can be foreseen and programs to solve them can be made, it still happens that human decisions have to be taken during the execution of the program. For this purpose the computer should be equipped with displays so that these decisions can be made without too much delay.

12.5 CONCLUDING REMARKS

Only the basic principles of the operation and design of a data processing station for flight testing could be reviewed. The main emphasis has been on medium-sized and large stations with a relatively large amount of automation, though many of the principles also apply to small-scale tests. A successful operation can only be realized when the planning of the data processing is started at a very early stage and when there is a very good co-operation between the flight test engineer, the instrumentation engineer and the computer specialist.

12.6 REFERENCES

1. D.J. Nowak, P.E. Schmid — Introduction to Digital Filters, IEEE Trans. on EMC, Vol. 10 no. 2, June 1968
2. A.V. Oppenheim, C.J. Weinstein — Effects of Finite Register Length in Digital Filtering and the Fast Fourier Transform, Proc. IEEE, Vol. 60 no. 8, August 1972
3. B. Gold, C.M. Rader — Digital Processing of Signals, McGraw Hill, 1969
4. Telemetry Standards, Document 106-71, Inter-Range Instrumentation Group, Range Commanders Council, White Sands Missile Range, New Mexico
5. Bruce T.Cameron — General Calculation Capability in a Production Data Reduction Environment-Batch Processing, Society of Flight Test Engineers Sponsored Symposium on Computer Aided Flight Testing, October 1970
6. J.J. Stinson — An Automatic Telemetry Data Acquisition System, presented at ISA Aerospace Instrumentation Symposium, Nevada, 1971

INDEX

A

AC amplifier 5.3
accessibility of the instrumentation equipment 2.8 - 8.12
accuracy 1.3 - 2.7 - 3.5 - 3.7 - 8.16
active bridge element 5.9
active filter 5.8
active transducer 4.6
adaptive filtering method 12.10
aliasing (error) 5.3 - 5.6 - 6.1 - 6.2 - 10.4
alignment of gaps 9.9
AM demodulator 5.11
amplification 5.2 - 5.3
amplifier noise 5.2
amplitude characteristics 3.8 - 9.6
amplitude error 6.5
amplitude modulation 5.9 - 10.3
amplitude response 3.8 - 6.4
analog computer 12.6 - 12.12
analog data-collection system 8.5
analog-to-digital conversion 5.3 - 5.13 - 5.14 - 12.5
analog filter interpolation 6.6
analog (magnetic) tape recorder 8.5 - 9.1
angular acceleration 4.3
angular vibration 4.3
antenna 10.7 - 10.9
anti-vibration mount 4.3
aperiodic damping 3.8
asynchronous sampling process 6.1
atomic oscillator 11.6
attenuation 5.2 - 5.3
attenuation of a transmitted wave 10.8
autocalibration (autocal) 7.5
automatic tracking 10.9
automatic test equipment (ATE) 8.11
automatic typewriter 12.7

B

backlash 7.5
band-pass filter 5.7
band-stop filter 5.7 - 6.12
bandwidth 9.7 - 10.3
battery buffering 8.14
bias 9.6
binary code 9.10
binomial filter 6.3 - 6.4
bit (packing) density 8.5 - 9.9
biphase code 9.10
blunder error 12.5
bonded-foil thermocouple 4.6
bonded-wire strain gage 4.7
break frequency 6.4
bridge (circuits) 5.2 - 5.9
brushless encoder 4.12
brushless synchro 4.11
brush-type encoder 4.12
built-in test equipment (BITE) 8.11
Butterworth filter 5.7 - 6.3 - 6.4

C

calibration 7.1 - 8.16 - 12.7
calibration error 3.6
calibration point 7.5
calibration standard-error 3.6
calibration table method 12.9
capacitive transducer 4.9 - 5.9
carrier 5.9 - 10.3
carrier centre frequency 9.8
case ground 8.13
certificated aircraft 1.1 - 1.7
charge amplifier 4.6 - 5.6
chassis ground 8.13
checklist 8.17
chopper amplifier 5.6
chromel-alumel thermocouple 4.6
circularly polarized antenna 10.9
closed-circuit television 8.3
closed-loop transducer 4.13
coarse and fine recording 8.4 - 12.9
common mode 5.4
common mode rejection (ratio) 5.4 - 5.5
commutation 5.12 - 8.7
compensation 5.2 - 5.8
compiler 12.13
complete calibration 7.1 - 7.2
component calibration 7.1
composite data collection system 8.3
compression-type piezoelectric transducer 4.6
computation 12.6
computer 12.12
computer-compatible tape 8.5 - 9.10 - 12.5 - 12.13
computer input/output (I/O) time 12.12
continuous modulation 10.3
conductive plastic-film potentiometer 4.7
continuous trace recorder 8.5 - 9.1 - 12.11
control synchro 4.11
convolution 12.10
copper-constantan thermocouple 4.6
correction 3.1
cost of an instrumentation system 2.6
counting 5.2
counting method 5.13
crash recording 8.4

critical damping 3.8
cross-axis sensitivity 4.1
cross talk 8.8 - 8.16
current amplifier 5.3
cut-off frequency 5.7 - 6.4

D

damping (-coefficient) 3.7 - 3.8
data analysis 1.3
data bank 1.8
data break point 6.7
data collection (sub) system 2.3 - 12.4
data compression 6.1 - 8.6
data input 12.2
data processing centre 12.2
data processing (sub) system 2.4 - 2.5
DC amplifier 5.3
dead band error 3.6
decommutation 5.12
demodulation 5.2 - 5.9 - 5.11
demultiplexer 10.1
deskewing 9.9
Desynn 4.7
development trial 1.5
differential amplifier 5.4
differential synchro 4.11
digital code 9.9
digital computer 12.6 - 12.12
digital interpolation 6.6
digital (magnetic) tape recorder 9.1
digital-to-analog conversion 5.12
digital transducer 4.12
direct recording 8.4 - 9.6
direct sensor 9.4
discrimination 5.12
distance measuring equipment 11.2
diversity reception 10.9
double-sideband 10.3
drift 5.6
drift error 3.6
dropout 9.10 - 10.1
DSB/FM telemetry system 10.6
dynamic accuracy 3.5 - 3.7
dynamic calibration 7.2 - 7.6
dynamic linearity 3.7 - 7.6
dynamic skew 9.9

E

electrical filter 4.3
electrical noise 8.12
electrical power 8.14
electrochemically sensitive paper 9.4
electronic commutator 8.8
electronic interferometer 11.2
electro-sensitive paper 9.4
electrostatic mosaic printer 12.7
electrostatic recorder 9.4
environmental calibration 7.2 - 7.7
environmental conditions 3.6 - 8.15
environmental parameters 3.4 - 4.1
environmental qualification 2.7
error of commission 6.1 - 6.2
error distribution 3.3
error of omission 6.1 - 6.3
event marker 9.4
events per unit time (EPUT) 5.13
experimental aircraft 1.7

F

fading 10.1 - 10.8
feedback transducer 4.13
filter 5.7
filtering 5.2 - 5.6 - 12.10
finesse 3.5 - 3.10 - 4.1 - 7.4
first-order data 6.10
first-order filter 6.5
first-order instrument 3.7
flight testing 1.1
flight test instrumentation 1.1
flip-flop circuit 5.12
flexibility 2.8
floating single-ended amplifier 5.4
flutter 9.6
FM/FM telemetry system 10.6
FM recording 9.8
foil strain gage 4.7
foldover error 6.7
foldover frequency 6.2
force-balance transducer 4.13
Fourier analysis 3.9
fourth-order data 6.11
frame synchronization 9.10
frequency 5.2
frequency band 10.7
frequency diversity 10.9
frequency division multiplexing 8.7 - 9.6 - 10.5
frequency generating transducer 4.11 - 4.12
frequency meter 9.4
frequency modulation 5.2 - 5.9 - 5.12 - 9.6 - 10.4
frequency response 4.3
frequency standard 11.6
fuel-level transducer 4.9
functional testing 8.16
fuselage-mounted camera 8.3

G

gain of transmitting antenna 10.8

Gauss filter 5.7 - 6.3 - 6.4
glassfibre cables 5.11
grounding 8.13
ground loop 5.4 - 5.6
ground recording 10.9
group delay 3.10 - 7.6

H

head assembly 9.5
head configuration 9.7
head stack 9.5
heater blanket 4.2
heat-sink 4.2
helical antenna 10.9
higher-order digital interpolation 6.6
higher-order filter 6.5
high-pass filter 5.7
hybrid computer 12.6
hysteresis 7.5 - 12.8
hysteresis error 3.2 - 3.6

I

impedance 5.2
indicated value 3.1
inductive transducer 5.9
infra red tracker 11.2
in-flight calibration 12.8
input characteristic 4.1
instrumentation checking 12.3 - 12.11
instrumentation design phase 2.1
instrumentation development phase 2.1
instrumentation test phase 2.1
integral heater 4.2
interaction 8.17
interference 8.13
intermediate band 9.8
International Standards System 7.3
interpolation error 3.6 - 6.2 - 6.5 - 6.6 - 6.9
interpolation filter 6.7 - 6.8
interpolation of data 6.5
interpretation of test results 12.7
inter-record gap 8.5 - 12.12
inverting amplifier 5.6
IRIG specifications 9.5 - 9.7 - 10.7 - 10.11
iron-constantan thermocouple 4.6

K

kinetheodolite 2.4 - 11.2

L

laser ranging equipment 11.2
Light Emitting Diode (LED) 5.11
limited calibration 7.2
linearity 3.4
linearly polarized antenna 10.9
linear interpolation 6.6
linear operation 5.2
linear phase filter 5.7
linear scale encoder 4.12
linear variable differential transformer 4.10
line of sight 8.4 - 10.8
line printer 12.7
long term stability 3.6
low band 9.8
low-pass filter 4.3 - 5.7 - 6.6
lumped-parameter filter 6.3

M

magnetic tape 9.5
magnetoelectric transducer 4.6 - 4.11
maintenance of flight test instrumentation 2.8 - 8.10
measured value 3.1
measurement 7.1
measurements list 2.3 - 8.1
measuring range 3.4 - 4.1
mechanical filter 4.3
memory cycle time 12.13
metal tape 9.5
modulation 5.9 - 10.2 - 10.6
modulation factor 10.3
modulation index 10.4
modulation method 12.12
monopulse tracking 10.9
moving-coil galvanometer 9.4
moving-magnet galvanometer 9.4
multi-mirror transducer 9.4
multipath propagation 10.8
multiplexer 10.1
multiplexing 8.7 - 10.2 - 10.4
multi programming 12.13

N

natural frequency 3.7
negative feedback 4.13
non-return to zero change 10.5
non-steady test 1.6
normal mode 5.4
notch filter 6.12
Nyquist diagram 3.8
Nyquist frequency 1.3
Nyquist sampling theorem 6.1
NRZ code 9.10

O

off-line quick look 12.3
on-board recording 8.3
on-line data processing 8.2 - 10.12 - 12.13

on-line quick look 12.3
on-off marker 9.4
operational amplifier 5.5
opto-electronic technology 5.11
output characteristic 4.3
overall calibration 7.8

P

PAM/FM telemetry system 10.6
parallax error 3.6
parallel digital signal 5.13
parallel recording 9.9
parameter list 1.7
parity bit 9.10
passband 6.2
passive bridge element 5.9
passive filter 5.8
passive transducer 4.7
PCM/FM telemetry system 10.6
pen recorder 9.2 - 9.4
performance monitoring 8.10
period 5.14
periodic sampling process 6.1
peripheral units 12.7
phase angle 5.2
phase characteristic 3.8
phase distortion 3.10
phase modulation 10.4
phase response 6.4
phase sensitive demodulator 5.11
phase shift 3.8 - 5.2
photo detector 5.11
photoelectric sensor 4.6 - 4.12
photographic recorder 9.3 - 9.4
photo panel recorder 8.5 - 9.1 - 12.11
photoresistive sensor 4.12
phototheodolite 11.2
piezoelectric transducer 4.6 - 5.6
piezoelectric effect 4.8
polarization diversity 10.9
polynomial method of calibration 12.9
postdetection recording 10.10 - 12.12
postflight check 7.8 - 8.17 - 12.3 - 12.9 - 12.11
potentiometer 4.7
power amplifier 5.3
power ground 8.13
preconditioning 8.9
predetection recording 9.8 - 10.10 - 12.12
preflight check 7.8 - 8.11 - 8.17 - 12.3 - 12.11
preprocessing 12.3
preprocessing computer 12.12
preprocessing phase 2.5
presampling filter 6.1 - 6.3 - 6.5 - 6.12
presentation of computer results 12.7
primary standard 7.1
probability distribution 3.2
pulse amplitude modulation 10.4
pulse code modulation 5.9 - 5.11 - 10.4
pulse duration modulation 5.9 - 5.10 - 9.6 - 10.4
pulse excitation 7.6
pulse generating transducer 4.11
pulse modulation 10.3
pulse phase modulation 10.4
pulse position modulation 10.4
pulse repetition rate signal 5.13
pulse stretching 6.6 - 6.9

Q

quantization error 3.3
quarz oscillator 11.6
quasi-static measurement 3.5
quick look 2.6 - 8.5 - 10.9 - 12.3 - 12.11
quick-look analysis 1.2 - 6.5

R

radiation 8.12
radio frequency link 10.7
ramp generator method 5.14
ramp input response 3.8
ratiometer 9.4
"read after write" method 8.11
reading error 3.6
receiving antenna 10.8
reciprocating tape transport 9.10
recovery time 3.4
redundancy reduction 6.1
reed relay 5.13
relay switch 5.13
reliability 2.7
remote multiplexing 8.10
resistance thermometer 4.8
resolver 4.11
resolution 3.5 - 3.6
response 3.7
roll-off 6.4
rosette-type strain gage 4.8
rough reading 3.1

S

sampling duration 6.2
sampling frequency 6.2 - 6.5
second-order data 6.10
second-order filter 6.5
second-order system 3.7
self calibration 12.3
self-clocking code 9.10
self-generating transducer 4.6
self-heating effect 4.8

self test 12.3
semiconductor strain gage 4.8
semi-digital transducer 4.11
sensitivity 3.4
serial digital signal 5.13
serial recording 9.9
servo compensating bridge 5.9
servo transducer 4.13
shaft (-position) encoder 4.12 - 5.15
shear type piezoelectric transducer 4.6
shielding 8.12 - 8.14
shock 4.2
short term stability 3.6
shuttle tape transport 9.10
side band 10.3
signal conditioning 5.1 - 8.8
signal conversion 5.2 - 5.9
signal ground 8.13
signal transformation 5.2
single-carrier FM recording 9.8
single-ended amplifier 5.4
single-sideband 10.3
sinusoidal excitation 7.6
sinusoidal response 3.8
skew 9.9
smoothing 12.5 - 12.10
source encoding 6.1
space diversity 10.9
SSB/FM telemetry system 10.6
stability check 8.16
stagnation temperature probe 4.8
standard 7.1 - 7.3
standard deviation 3.3
static accuracy 3.6
static calibration 3.1 - 7.2 - 7.3
static linearity 3.5
static skew 9.9
step input response 3.7
step interpolation 6.6
storage of data 12.2
strain gage 4.7
subcarrier 9.8 - 10.2
subcommutation 8.8 - 10.5
subordinate standard 7.1
successive approximations method 5.14
supercommutation 8.4 - 8.8 - 10.5
synchro 4.10 - 5.2 - 5.11
synchro control transformer 4.11
synchro control transmitter 4.11
synchronization character 9.10
synchronization of measuring systems 11.7
synchrotel 4.11
synchro-to-phase converter 5.11
synchro torque receiver 4.10
synchro torque transmitter 4.10
synchro with fixed coils 4.11
system integration 8.11 - 8.16

T

take-off camera 11.5
take-off and landing measurements 11.5
tape drive mechanism 9.5
tape format 9.9 - 9.10
tape identification 9.10
tape recorder 9.5
tape speed 9.6
tape width 9.7 - 12.11
Tchebycheff filter 5.7
telecommand link 10.1
temperature compensation 4.2
temperature-controlled compartment 4.2
temperature gradient 4.2
temperature transient 4.2
test 1.1
thermistor 4.8
thermoelectric transducer 4.6
third-order data 6.11
time base 11.8 - 12.5 - 12.10
time constant 3.7
time correlation 8.6 - 12.5 - 12.10
time-division multiplexing 8.7 - 9.6 - 10.5
time format 11.6
time standard 11.6
traceability 7.3
track arrangement 12.11
tracking 10.9
tracking radar 11.3
trajectory measuring system 11.1
transducer alignment error 4.2
transducer location error 4.2
transducer with digital output 4.4
transducer with pulse output 4.4
transfer characteristic 4.2
transfer function 3.9
transmission channel 10.2
transmission antenna 10.8
true differential amplifier 5.4
turnstile antenna 10.9
twisting 8.12 - 8.14

U

ultra-violet recorder 9.3
unbonded wire strain gage 4.8
uncertificated aircraft 1.1 - 1.5
unique pattern 9.10

V

validation of computer operations 12.7

variable capacitance transducer 4.9
variable differential transformer 4.10
variable impedance transducer 5.10
variable inductance transducer 4.9
variable resistance transducer 4.7
vibrating-wire transducer 4.12
vibration 4.2
vibration isolation mount 4.3
visual curve fitting 6.5
voltage amplifier 5.3
voltage-controlled oscillator 5.10

W

wavelength 10.8
wave propagation 10.8
Wheatstone bridge 5.8
wideband 9.8
Wiener optimum slope 6.10
wool tuft pattern 8.3
word 9.9
word synchronization 9.10
wow 9.6

Z

zero error 3.6
zero offset 5.6
zero shifting 5.2 - 5.8
zero suppression 5.8