AGARD-AG-300 Vol.9

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AGARD

ADVISORY GROUP FOR AEROSPACE RESEARCH & DEVELOPMENT

7 RUE ANCELLE 92200 NEUILLY SUR SEINE FRANCE

AGARDograph No.300

AGARD Flight Test Techniques Series
Volume 9
on
Aircraft Exterior Noise Measurement and Analysis Techniques

(Le Bruit à l'Extérieur des Aéronefs: Techniques de Mesure et d'Analyse)

NORTH ATLANTIC TREATY ORGANIZATION

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Flight Test Techniques Series - Volume 9

Aircraft Exterior Noise Measurement and Analysis Techniques

(Le Bruit à l'Extérieur des Aéronefs: Techniques de Mesure et d'Analyse)

by

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Preface

Since its founding in 1952, the Advisory Group for Aerospace Research and Development has published, through the Flight Mechanics Panel, a number of standard texts in the field of flight testing. The original Flight Test Manual was published in the years 1954 to 1956. The Manual was divided into four volumes:

1 Performance
2 Stability and Control
3 Instrumentation Catalog, and
4 Instrumentation Systems.

As a result of developments in the field of flight test instrumentation, the Flight Test Instrumentation Group of the Flight Mechanics Panel was established in 1968 to update Volumes 3 and 4 of the Flight Test Manual by the publication of the Flight Test Instrumentation Series, AGARDograph 160. In its published volumes AGARDograph 160 has covered recent developments in flight test instrumentation.

In 1978, the Flight Mechanics Panel decided that further specialist monographs should be published covering aspects of Volume 1 and 2 of the original Flight Test Manual, including the flight testing of aircraft systems. In March 1981, the Flight Test Techniques Group was established to carry out this task. The monographs of this Series (with the exception of AG 237 which was separately numbered) are being published as individually numbered volumes of AGARDograph 300.

At the end of each volume of both AGARDograph 160 and AGARDograph 300 two general Annexes are printed. Annex 1 provides a list of volumes published in the Flight Test Instrumentation Series and in the Flight Test Techniques Series. Annex 2 contains a list of handbooks that are available on a variety of flight test subjects, not necessarily related to the contents of the volume concerned.

The present Volume (Vol.9 of AGARDograph 300) describes testing and analysis techniques to measure aircraft noise primarily for purposes of noise certification as specified by the 'International Civil Aviation Organization', ICAO. The relevant aircraft noise certification 'Standards' and 'Recommended Practices' are presented in detail for subsonic jet aeroplanes, for heavy and light propeller-driven aeroplanes and for helicopters. The practical execution of conducting noise certification tests is treated in depth. The characteristics and requirements of the acoustic and non-acoustic instrumentation for data acquisition and data processing are discussed, as are the procedures to determine the special noise measures 'Effective Perceived Noise Level' (EPNL) and 'Maximum Overall A-weighted Noise Level' ($L_{pA,max}$) that are required for the noise certification of different types of aircraft.

The AGARDograph also contains an extensive — although selective — discussion of test and analysis techniques for more detailed aircraft noise studies by means of either flight-experiments or full-scale and model-scale wind tunnel experiments.

Préface

Depuis sa création en 1952, le Panel de la Mécanique du vol, sous l'égide du Groupe Consultatif pour la Recherche et les Réalisations Aérospatiales a publié, un certain nombre de textes qui font autorité dans le domaine des essais en vol. Le Manuel des Essais en Vol a été publié pour la première fois dans les années 1954—1956. Il comportait quatre volumes à savoir:

1 Performances
2 Stabilité et Contrôle
3 Catalogue des appareils de mesure, et
4 Systèmes de mesure.

Les novations dans le domaine des appareils de mesure pour les essais en vol, ont conduit à recréer, en 1968, le groupe de travail sur les appareils de mesure pour les essais en vol pour permettre la remise à jour des volumes 3 et 4. Les travaux du groupe ont débouché sur l'édition d'une série de publications sur les appareils de mesure pour les essais en vol, l'AGARDographie 160. Les différents volumes de l'AGARDographie 160 publiés jusqu'à ce jour couvrent les derniers développements dans le domaine.

En 1978, le Panel de la Mécanique du vol a signalé l'intérêt de monographies supplémentaires sur certains aspects des volumes 1 et 2 du Manuel initial et notamment les essais en vol des systèmes avioniques. Ainsi, au mois de mars 1981, le groupe de travail sur les techniques des essais en vol a été recréé pour mener à bien cette tâche. Les monographies dans cette série (à l'exception de la AG 237 qui fait partie d'une série distincte) sont publiées sous forme des volumes individuels de l'AGARDographie 300.

A la fin de chacun des volumes de l'AGARDographie 160 et de l'AGARDographie 300 figurent deux annexes générales. L'annexe 1 fournit la liste des volumes publiés dans la série "Appareils de mesure pour les essais en vol" et dans le série "Techniques des essais en vol". L'annexe 2 donne la liste des manuels disponibles sur les mêmes thèmes dans le domaine des essais en vol, qui ne sont pas forcément en rapport avec le contenu du volume en question.

Ce volume 9 de l'AGARDographie 300 décrit les techniques d'essai et d'analyse mises en oeuvre pour le calcul du bruit généré par les aéronefs, principalement aux fins de la certification acoustique, conformément aux indications de l'Organisation de l'Aviation Civile Internationale (OACI). Les normes et les pratiques recommandées appropriées dans le domaine de la certification acoustique des aéronefs sont présentées dans le détail, pour ce qui concerne les avions à réaction subsoniques, les avions à turbopropulseur lourds et légers et les hélicoptères. Les aspects pratiques de la réalisation des essais en vue de l'homologation acoustique sont traités de facon approfondie. Les caractéristiques et les spécifications des appareils de mesure acoustiques pour la saisie et le traitement des données sont examinés, ainsi que les procédures adoptées pour les calculs spécifiques du "niveau effectif de bruit percu" (EPNL) et du "niveau maximal global de bruit pondéré A" ($L_{pA,max}$) qui sont demandés pour la certification acoustique de différents types d'aéronefs.

Cette AGARDographie présente également une synthèse à la fois approfondie, judicieuse et très détaillée des techniques d'essais et d'analyse propres à des études de bruit faisant appel à des essais en vol ou en soufflerie soit à vraie grandeur, soit à échelle réduite.

Acknowledgement
to
Working Group 11 Members

In the preparation of the present volume the members of the Flight Test Techniques Group listed below took an active part. AGARD has been most fortunate in finding three competent people willing to contribute their knowledge and time in the preparation of this and other volumes.

La liste des membres du groupe de travail sur les techniques des essais en vol ont participé activement à la rédaction de ce volume figure ci-dessous. L'AGARD peut être fier que ces personnes compétentes aient bien voulu accepter de partager leurs connaissances et aient consacré le temps nécessaire à l'élaboration de ce et autres documents.

Adolph, C.E.		OSD/US
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Member, Flight Mechanics Panel
Chairman, Flight Test Techniques Group

Foreword

It was Dr Helmut Bothe of DLR, longstanding member of Working Group 11 of the AGARD Flight Mechanics Panel, who first suggested to me to write an AGARDograph on 'Aircraft Noise Measurement Analysis Techniques'. Being overjoyed, and quite honoured, I readily agreed to his and AGARD's proposal. Had I known what I'd been in for, I probably would not have agreed quite so enthusiastically. And yet, it has been an experience which I would not want to miss, and for this reason, among others, I am quite thankful to him in particular, and to AGARD's Flight Mechanics Panel in general.

In the course of time, I experienced much help in one way or another by many individuals. Foremost, I'd like to thank Mr Anthony Pool, my first editor, who steered me along the right track and who undertook the admirable task of going through the (initial) version of the AGARDograph word by word. My second editor, Professor Braga da Costa Campos, too provided many helpful suggestions. Mr Michael Foster of AGARD gave me much encouragement along the way.

There have been numerous other people from whom I experienced help and with whom I had fruitful discussions. Among these were

- in Canada: Alan Massey of Transport Canada and Robert Westley of the National Research Council;
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Geographically somewhat closer, I'd also like to thank my colleagues in the DLR, most notably Helmut Dahlen, Werner Dobrzynski (much of his original artwork appears in this AGARDograph), Michael Kallergis, Klaus-Jürgen Schultz and Wolf Splettstoesser, all of whose research material I freely used.

Finally, my thanks go to my trusted secretary, Miss Kerstin Ehlers, who assisted me perfectly — especially in the final phase of completing the AGARDograph.

Hanno Heller
Braunschweig
December 1990

Contents

List of Figures

<u>Figures in the Appendices</u>

Terms and Abbreviations

AC	Alternating Current
ACA	Airworthiness Certificate Application
A/D	Analog to Digital
AIR	Aerospace Information Report
ANNEX 16	International Standards and Recommended Practices "Environmental Protection", ANNEX 16 to the Convention on International Civil Aviation
APU	Auxiliary Power Unit
ARINC	(Multiplexer Unit) by Aeronautical Radio Inc
BMV	German Ministry of Transportation
BNC	Designation for type of shielded coaxial cable
BPF	Blade passage Frequency
BVI	Blade/Vortex Interaction
CAA	(British) Civil Aviation Authority
CAEP	Committee on Aviation Environmental Protection (Body of ICAO)
CAEP/1	First Meeting of CAEP (in 1986)
CAN	Committee of Aircraft Noise (Body of ICAO)
CAN/1	First Meeting of CAN
CAN/2	Second Meeting of CAN, etc
CAS	Calibrated Airspeed
CRP	Counter-rotating Propeller
D	10-dB-down time (duration correction factor)
D/A	Digital to Analog
DC	Direct Current
DLR	Deutsche Forschungsanstalt für Luft- und Raumfahrt
DNW	Deutsch-Niederländischer Windkanal (German Dutch Wind Tunnel)
DOT	(US) Department of Transportation
DR	Direct Recording
EDVE	Designation of Braunschweig Airport
EPNL	Effective Perceived Noise Level (also sometimes called L_{EPN}), in units of EPNdB
FAA	US-Federal Aviation Authority
FFT	Fast Fourier Transform
FM	Frequency modulated
GA	General Aviation
GMT	Greenwich Mean Time
HTM	Helical Propeller Blade-tip Mach-number (also sometimes called M_{hel})
HPDA	Heavy Propeller-driven Aeroplanes - refers to propeller-driven aeroplanes over 5700 kg or 9000 kg, respectively, maximum certificated take-off mass
HPNOR	Highest Power in the Normal Operating Range
HS	High Speed (used in the context of rotor impulsive noise)
IAS	Indicated Airspeed
ICAO	International Civil Aviation Organisation

INS	Inertial Navigation System
IRIG	Inter Range Instrumentation Group (type of recording bandwidth)
ISA	International Standard Atmosphere
ISLM	Integrating Sound Level Meter
KTH	Kinetheodolite
LED	Light Emitting Diode
LPDA	Light Propeller-driven Aeroplanes - refers to propeller-driven aeroplanes not exceeding 5700 kg or 9000 kg, respectively, in maximum certificated take-off mass
L_{EPN}	Effective Perceived Noise Level (also sometimes called EPNL), in units of EPNdB
L_{pAE}	1-second equivalent energy noise level (also called Sound Exposure Level, SEL and previously often termed L_{AX}), in units of dB
M_{adv}	Advancing (rotor blade tip) Mach number
MAPS	Microwave Airplane Positioning System
M_{hel}	Helical Propeller Blade-tip Mach-number (also sometimes called HTM)
MCP	Maximum Continous (Engine) Power
MCTOW	Maximum Certificated Take-off Weight
MCTOM	Maximum Certificated Take-off Mass
MNOP	Maximum Normal Operating Power
MPNOR	Maximum (Engine) Power in the Normal Operating Range
NASA	(US) National Air and Space Administration
NGTE	(British) National Gas Turbine Establishment
NLR	(Dutch) Nationaal Lucht- en Ruimtevaartlaboratorium
NPD	Noise/Power/Distance
OASPL	Overall Sound Pressure Level
OBP	On-board Processor
PAPI	Precision Approach Path Indicator
PCM	Pulse Code Modulated
PDA	Propeller-driven Aeroplane
PNL	Perceived Noise Level, in units of PNdB
PNLT	Tone-corrected Perceived Noise Level, in units of TPNdB
PNLTM	Maximum Value of the Tone-corrected Perceived Noise Level (occuring during a flyover) in units of TPNdB
POP	Photo Overhead Positioning (System)
PSLM	Precision Sound Level Meter
PTB	Physikalisch-Technische Bundesanstalt
PTH	Pressure Time History (also referred to as 'Wave Form')
R/C	Rate of Climb
RH	Relative Humidity
RMS	Root Mean Square
RPM	Rotational Speed per Minute
RTA	Real Time Analyser
SAE	Society of Automotive Engineering

SARP	Standard and Recommended Practice (i.e. the ICAO ANNEX 16 document)
SEL	Sound Exposure Level
S/N	Signal to Noise (Ratio)
SLM	Sound Level Meter
SLNS	Side line noise level
SSD	Start/stop Detector
STOL	Short Take-off and Landing Aircraft
STR	Strouhal Number (dimensionless frequency)
T	Ambient Air Temperature
TAS	True Airspeed
TISG	Technical Issues Sub Group (Body of ICAO)
TNT	Tragflügel Neuer Technologie
TOM	Take-off Mass
TOP	Take-off Power
TOW	Take-off Weight
UHF	Ultrahigh Frequency (Range)
UTC	Universal Time Code
VHF	Very High Frequency (Range)
WG	Working Group within CAN or CAEP
WHL	Westland Helicopter Ltd. Company

Symbols

a	speed of sound (m/s)
c	speed of sound (m/s)
c_p	power coefficient
C(t) or C(k)	tone correction factor (dB)
d	distance (m)
D	propeller diameter (m)
D	duration correction factor (≙ "10-dB-down time") (dB)
D	distance to clear 15 m high obstacle after brake-release at take-off
f	degree of freedom, N-1
F_N	net thrust (N)
h	microphone height above ground (m)
H	height above ground (usually of aircraft) (m)
i	band number of spectrum
k	denotation of flyover number
K	proportionality constant
L_p	sound pressure level (dB)
L_{pA}	A-weighted sound pressure level (dB)
L_{pAE}	sound exposure level (dB)
L_{pAS}	A-weighted sound pressure level measured with detector time constant 'slow' (dB)
M	Mach-number = V/c
M_{hel}	helical propeller blade tip Mach-number
n	Perceived Noisiness (noy)
n(k)	largest value of Perceived Noisiness (noy)
n(i;k)	band(i)-related Perceived Noisiness of the k^{th} flyover (noy)
N	sample size (e.g. total number of flyovers)
N	rotational speed (s^{-1})
N(k)	total Perceived Noisiness of k^{th} flyover (noy)
p	sound pressure level (N/m²)
P	engine power (W)
QK	measurement distance (m)
Q_rK_r	reference distance (m)
r	distance (m)
r	Repeatability
R	Reproducibility
s	standard deviation of a sample
s^2	variance of a sample
S	dimension
$t_{f;\alpha}$	test quantity in statistical evaluations after 'Student'
t_1	time instant when PNLT first exceeds (PNLTM-10) (s)
t_2	time instant after which PLNT remains less than (PNLTM-10) (s)

T	ambient air temperature (°C or K)
T	time constant (for EPNL-computation 10 s; for L_{AE}-computation 1 s)
T	tone burst repetition rate (s)
u_p	confidence limit (dB)
V	flight speed or tunnel flow speed (m/s)
V_b	propeller blade tip rotational speed (m/s)
V_H	airspeed in level flight using torque at minimum installed, maximum continuous engine power (m/s)
V_{NE}	never exceed speed (m/s)
V_s	stalling speed of aircraft (m/s)
V_y	speed for best climb (m/s)
V_∞	flight speed or wind tunnel flow speed (m/s)
V_2	safe take-off speed (m/s)
$\bar{x}$	mean of a sample

<u>Greek letters</u>

α	per unit length atmospheric sound attenuation (dB/100m)
α	error probability
β	blade pitch angle (degrees)
$\Delta\beta$	local blade incidence angle (degrees)
Δ	"Delta" a correction term
θ	angle between flight path and sound emission direction ("emission angle" (degrees)
λ	wave length (m)
μ	advance ratio
μ	mean of the total population
ρ	air density (kg/m^3)
σ	standard deviation of the total population
σ^2	variance of the total population
σ_r^2	within test variance
σ_T^2	between test variance
σ_R^2	reproducibility variance
τ	detector time constant (s)
ϕ	propeller rotational plane inclination (degrees)
ω	angular velocity (s^{-1})
ψ	azimuthal angle (degrees)

AIRCRAFT EXTERIOR NOISE MEASUREMENT AND ANALYSIS TECHNIQUES

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Summary

This AGARDograph describes testing and analysis techniques to measure aircraft noise primarily for purposes of noise certification as specified by the 'International Civil Aviation Organization', ICAO. The relevant aircraft noise certification 'Standards' and 'Recommended Practices' (as defined in ICAO "ANNEX 16") are presented in detail for subsonic jet aeroplanes, for heavy and light propeller-driven aeroplanes and for helicopters. The practical execution of conducting noise certification tests is treated in depth. The characteristics and requirements of the acoustic and non-acoustic instrumentation for data acquisition and data processing are discussed, as are the procedures to determine the special noise measures 'Effective Perceived Noise Level' (EPNL) and 'Maximum Overall A-weighted Noise Level' ($L_{pA,max}$) that are required for the noise certification of different types of aircraft.

This AGARDograph also contains an extensive - although selective - discussion of test and analysis techniques for more detailed aircraft noise studies by means of either flight-experiments or full-scale and model-scale wind tunnel experiments.

Appendices to this AGARDograph provide supplementary information on certain aspects of noise certification, such as the calculation of the Effective Perceived Noise Level, a discussion of an "acoustical change"-evaluation and the attainable precision of flyover noise measurements, a comparative representation of noise certification specifications according to types and categories of aircraft, tables concerning the atmospheric sound attenuation and a discussion on the validity of aircraft noise data, as obtained through very few flyover measurements. Definitions of several notions related to noise testing and analysis are also provided.

1. INTRODUCTION

1.1 Scope of AGARDograph

This AGARDograph on aircraft noise measurement and analysis techniques is primarily intended to assist the flight test engineer in his effort to prepare, conduct and evaluate a test program for the determination of the noise radiated by flight vehicles in compliance with established noise certification procedures.

Aircraft noise certification has but one objective: to determine an aircraft-specific noise certification level to be assessed against a given noise limit. For this purpose the aircraft to be tested flies over one or several microphones, positioned directly under the flight path or to the side of the flight track. Depending on the type or category of the aircraft, it must execute a number of level flyovers at a specified height or take offs or landing approaches (or all of these) at precisely defined operational conditions. The flyover noise is measured and corrected for any deviations from the reference flight path or reference operational and atmospheric conditions that may have occurred during the test. For each of these flight procedures, the corrected flyover noise levels are then averaged over all valid test-flyovers, to yield the final "certification level".

Although the ICAO-specifications within any particular test procedure require only four (six at most) "valid" flyovers, seemingly a rather minor effort, certification testing is in reality a very involved, laborious and time-consuming undertaking. Surveying and preparation of the test site, equipment selection, check, set-up and calibration, pretest familiarization flights for the benefit of the pilots and the measurement crew, detailed weather observation in addition to the sometimes extremely complex acoustic and non-acoustic data acquisition in the field, as well as the subsequent data analysis require a very good overall understanding of the entire procedure by the responsible test engineer. It is for this reason that this AGARDograph treats all relevant subjects in rather great - and hopefully sufficient - detail to provide the test engineer with enough guidance to plan and conduct a well thought-out noise certification test.

The scope of this AGARDograph goes, however, beyond the certification aspects. If an aircraft does not pass a noise test, it is important to understand why this "failure" occurs. In such a case it is often helpful to identify and isolate those particular sources that are responsible for the "excess" noise. Dedicated flight noise tests are indicated that will sometimes also provide information on changes in the aircraft configuration or in the propulsion system which can reduce the acoustic radiation. Such tests are usually more comprehensive and cover a much broader range of parametric variations than would be necessary for certification purposes.

Comprehensive flight noise tests are, however, inherently expensive. There sometimes are other - less involved - test techniques to obtain the required information, such as "equivalent testing procedures" (still using real aircraft) or scale-model tests - at times even full-scale - in appropriate wind tunnels. Tunnel testing - in the author's opinion - plays an important role in furthering the understanding of the aeroacoustics of individual aircraft-related noise generators (propellers, rotors, jets). Such in-depth testing will not only provide data for improving certification procedures and making them more efficient and accurate, but will - in the end - perhaps even allow the establishment of more stringent noise limits that are based on technical progress rather than wishful thinking. Discussing in detail the advantages and disadvantages of flight and wind tunnel experiments using selected examples that are not specifically undertaken in the context of noise certification testing and analysis is therefore also considered an important objective of this AGARDograph.

1.3 Content of AGARDograph

This AGARDograph deals with flight vehicles only, specifically with fixed-wing subsonic aircraft and helicopters. It is restricted to exterior noise as radiated individually from these types of aircraft. The measurement of interior noise in the aircraft and the vast area of noise contouring around airports are outside the scope of this AGARDograph. The subject is treated in three major sections:

- Noise Certification of Aircraft - Legislative Aspects: ICAO-ANNEX 16;
- Noise Certification Flight Testing and Analysis Techniques;
- Flight and Wind Tunnel Noise Testing for Research and/or Development Purposes.

The first Section discusses the legal aspects and a number of technical and procedural aspects in the noise certification of subsonic jet aeroplanes, heavy propeller-driven aeroplanes, light propeller-driven aeroplanes and helicopters, as specified by the International Civil Aviation Organisation.

The second Section treats - in greater depth - test and analysis techniques for the noise certification of these types of aircraft. Starting with acoustic and non-acoustic (meteorological and flight-tracking) instrumentation, this section continues with a discussion of test preparation, equipment selection and laboratory pre-checks, including aspects of the optimum test-site selection, equipment deployment, field-communication, test-execution, data acquisition and on-line data reduction, to conclude with off-line (laboratory) data analysis and interpretation.

The third Section deals with special flight experiments employing subsonic jet-aeroplanes, propeller-aircraft and helicopters and with corresponding jet, propeller and rotor experiments in wind-tunnels. This section illustrates how flight and wind-tunnel tests can help to investigate flight noise problems that go beyond the scope of a standard noise certification test.

Appendices to this AGARDograph discuss (A) the calculation of the 'Effective Perceived Noise Level', (B) the statistically correct evaluation of "acoustical changes" on aircraft and the precision of fly-over noise measurements and (C) commonalities and differences in the noise certification of aircraft according to type and category. Additional Appendices provide (D) atmospheric attenuation coefficients as function of humidity and temperature which are necessary to compute the attenuation of sound as it propagates through the atmosphere, and deal with (E) the establishment of the validity of flyover noise test results.

Specials sections at the end of this AGARDograph explain acoustical terms and symbols used.

1.3 Disclameur

Names of manufacturers and of technical equipment are given only for purposes of illustration and as typical examples. Naming equipment suppliers and special items is not intended as an endorsement for certain products. Equipment of comparable quality is available from other manufacturers.

2. NOISE CERTIFICATION OF AIRCRAFT

2.1 Introduction

The noise generated by an aircraft undergoes significant changes as it propagates towards an observer on the ground. In general terms, the "art" of measuring aircraft noise lies in properly accounting for the effects of all non-noise-source-related disturbances in order to determine the "true" source noise level (i.e. the noise as emitted by the aircraft). Only on the basis of the accurately determined true source noise (whereby the degree of accuracy required may well vary) will it be possible - for example - to make noise-comparisons between aircraft.

In noise certification it is, however, the noise as received by an observer standing on the ground and listening to an aircraft in flyover (i.e. the immitted noise) that is of primary interest. In this case the source directivity and the distance aircraft/observer at the time when the acoustic signal is emitted must be accounted for. The noise from an aircraft is not necessarily loudest when the aircraft is directly overhead; aircraft noise frequently reaches a maximum when the aircraft is approaching or receding. Moreover, atmospheric and spherical spreading losses account for the attenuation of sound as it propagates away from the aircraft; hence distance has a significant effect on the noise level as observed on the ground.

There are numerous additional influences that may have affected the noise before it reaches the observer's ear (or the microphone): wind may have blown the noise towards or away from the observer, nearby reflecting surfaces, such as buildings or trees, or - quite importantly - the ground the observer stands on, may increase or reduce the noise. Atmospheric turbulence of different scale refracts and scatters the sound waves, as may temperature-gradients along the sound propagation path. Atmospheric humidity may absorb some sound frequencies more than others, thus changing the spectral characteristics of the sound. All these parameters are aircraft-independent; they must be evaluated and understood in their quantitative effects to eliminate their influence.

In addition, ever present background noise mingles with the aircraft noise, at times even obscuring it and making its detection (and measurement) difficult. Wind may also affect the path of the aircraft itself, especially if the aircraft is light in weight. In that case the instantaneous distance of the aircraft to the observer changes sometimes in a rather erratic manner.

Fig. 2.1 illustrates the typical scenario for measuring aircraft noise and provides some feel for the "hardship", the test engineer will be in for.

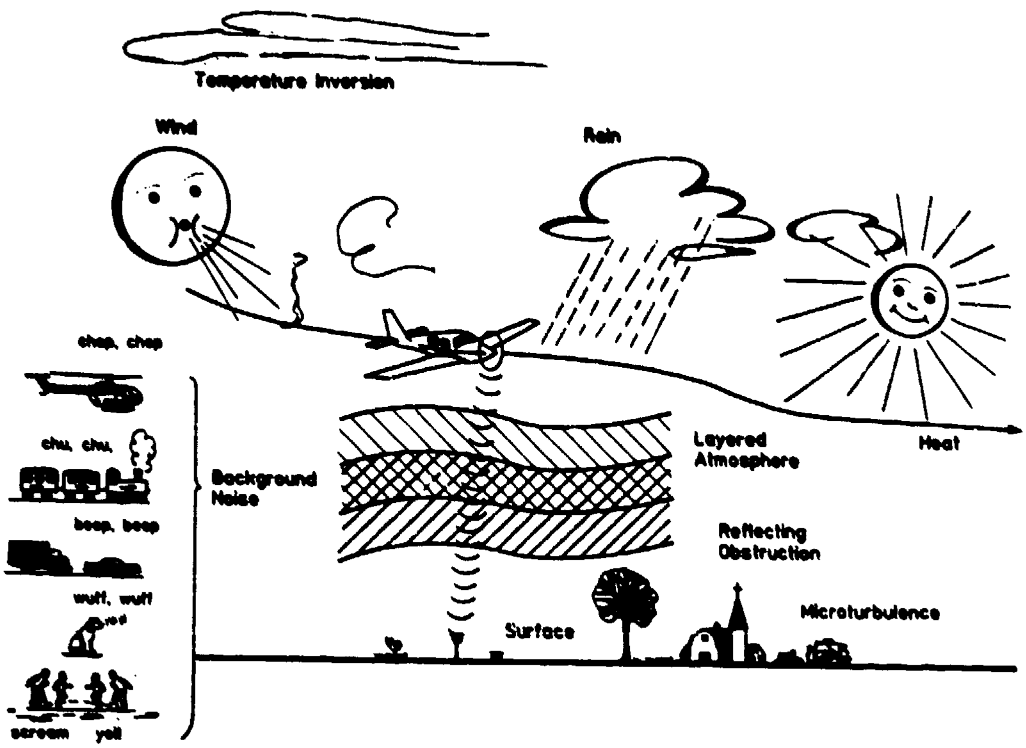


Fig. 2.1 Aircraft noise measurement scenario

Aircraft noise is also influenced at the source by ambient conditions: for example, temperature partially determines the Mach-number (ratio of a typical speed, such as a flight speed or a rotational speed and the ambient speed of sound in air) which in turn affects the noise generation process of an aircraft-propeller or of a helicopter-rotor; air-pressure affects the power and thus the noise-output of piston- or gas-turbine-engines or may influence the thrust of a jet engine and thus again the noise.

As stated already, in the process of aircraft noise certification the noise level must be determined as it occurs on the ground, with the effects of all non-aircraft related parameters accounted for including the distance (i.e. spherical spreading attenuation effects). Since the noise is measured on the ground, rather than in the immediate neighborhood of the flying aircraft (which is sometimes the better approach), all such parameters must be determined and appropriate corrections be applied in order to obtain a characterizing noise level of the aircraft. How this is done, is largely the subject of this AGARDograph.

For this purpose the immitted acoustic signal from the aircraft flying overhead must be measured over a sufficiently extended flyover time and over a wide frequency range using one or several microphones that are positioned along or orthogonal to the aircraft's flight path, depending on the type or category of the aircraft. Normally, the sound-signals are recorded for later laboratory analysis. During the actual measurement the aircraft must follow a precisely specified flight-path. At the same time the important aircraft flight and operational parameters are monitored and meteorological information is gathered at the test site and along the sound propagation path.

The transient and unsteady sound signal will usually be processed in one of two ways. For light propeller-driven aircraft, for example, only the 'maximum A-weighted noise level, $L_{pA,max}$' during flyover is of interest. Determination of the $L_{pA,max}$ requires next to no analytical effort. In principle it can be obtained directly from a visual read-out on a (precision) sound level meter, either on-line in the field or off-line in the laboratory from the recorded data. Only minor corrections are necessary to arrive at the actual certification noise level. Heavy propeller-driven aeroplanes, subsonic jet aircraft and helicopters, on the other hand, are acoustically evaluated in terms of the 'Effective Perceived Noise Level, EPNL'. Determination of the EPNL necessitates a computer and is a fairly complex analytical procedure. Computation of the EPNL will be explained in detail in Appendix A to this AGARDograph and the reader is encouraged to refer to this Appendix whenever the subject of noise measures is encountered. An example of an EPNL determination will also be provided in Section 3.6.2 of this AGARDograph. A very brief explanation of the two noise measures L_{pA} and EPNL is given in the following:

The human auditory system responds to frequencies from approximately 16 Hz to 16000 Hz. The ear's sensitivity varies, however, with frequency: it is rather insensitive at very low and very high frequencies, but very sensitive at frequencies in between. This is exemplified in Fig. 2.2 where

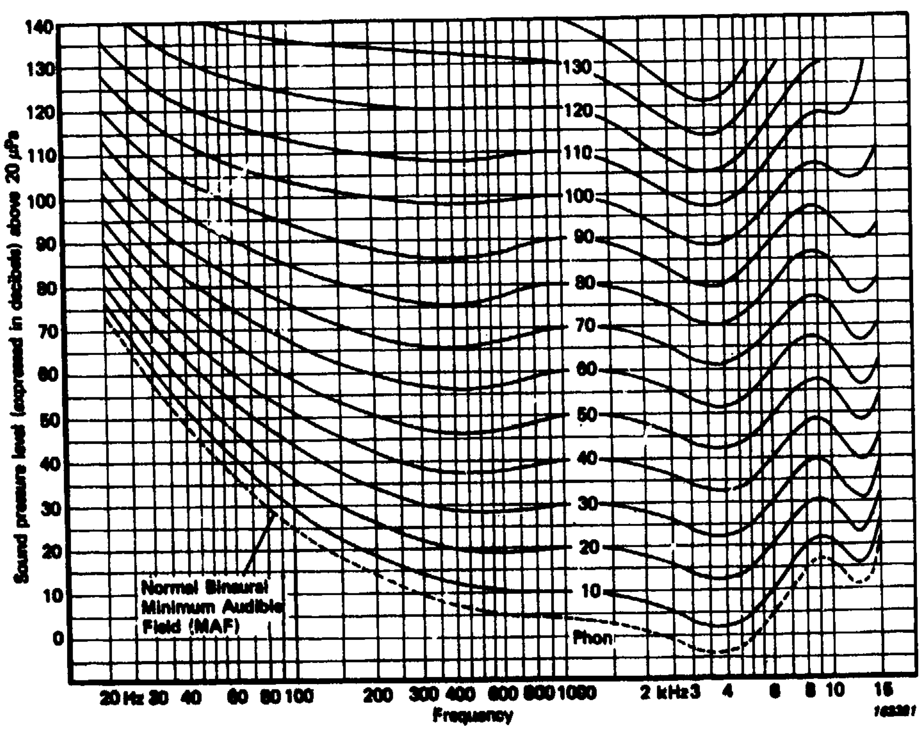


Fig. 2.2 Contours of equal loudness

contours of equal loudness for pure tones are shown. For example, a 1000 Hz tone of 50 dB appears as loud as a 20 Hz tone of 95 dB or as a 8000 Hz tone of 57 dB. The ear is most sensitive between 3000 and 4000 Hz.

This sensitivity is now accounted for by the A-weighting curve (which is a very rough approximation of an inverse loudness contour), as shown in Fig. 2.3. A-weighting thus de-emphasizes spectral portions below 800 Hz and above 5000 Hz, while emphasizing those in the frequency range from 1000 Hz to 4000 Hz, without regard, however, to the absolute noise level. Subjecting any noise to A-weighting therefore emphasizes the most sensitive frequency regime of the human auditory system. It is worth mentioning that the noise measure 'L_{pA}' correlates rather well with "annoyance" caused by noise, which is frequently defined as "unwanted sound". There are other weighting curves, such as C-weighting which is sometimes used to de-emphasize the very low frequencies (such low frequencies may be a problem on a microphone in the open when the wind blows at it).

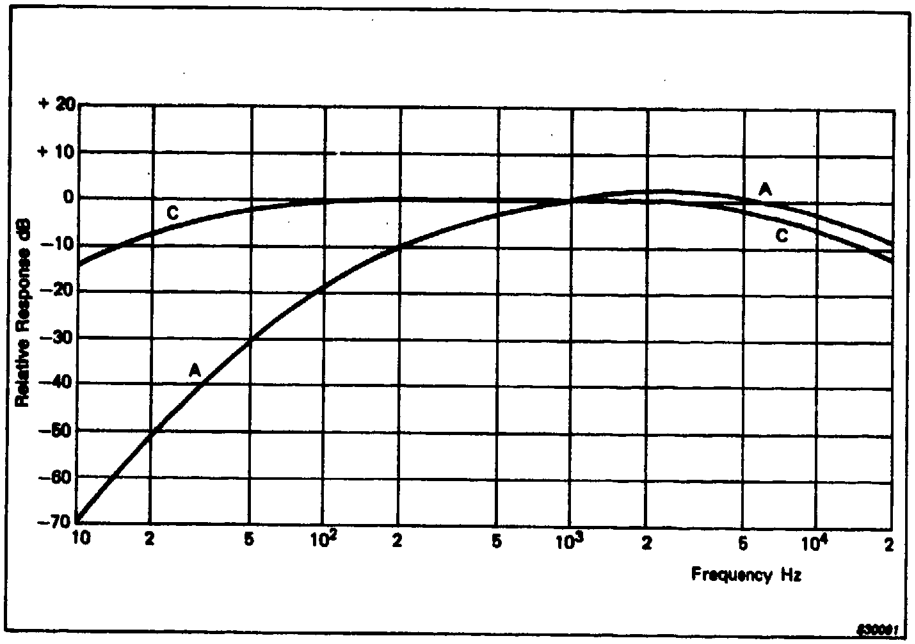


Fig. 2.3 A-weighting and C-weighting Curves (Frequency Response Characteristics of SLMs)

Computation of the EPNL requires the determination of sound pressure level 1/3-octave band spectra over a large frequency range (from at least 25 Hz to 10000 Hz) at 0.5-second fixed time intervals over a time span that covers the period where the aircraft's flyover noise is within 10 to 15 dB below the maximum. Each of these spectra (typically between 30 and 60 for each flyover event) is individually subjected to a level-dependent noise-weighting - somewhat different from an A-weighting but again in correspondence to the human perception of sound. Each spectrum is further individually corrected for distance effects (since the actual distance aircraft/observer continually changes during the flyover) and for atmospheric attenuation effects; finally an adjustment is made for the presence of pronounced tones within each spectrum to arrive at the composite noise-measure. Obviously, the EPNL cannot readily be determined on-line in the field, but requires data storage and off-line computer analysis. Modern equipment allows, however, the determination of an EPNL-value in near real time, so that the validity of a flyover event - as far as the final noise measure is concerned - can be established within a few minutes of the test.

It should be well understood that in measuring aircraft flyover noise one cannot expect the same accuracy and repeatability as in other areas, such as in aircraft performance measurements, for example. In fact the question of repeatability in flyover noise measurements is a very serious issue and the quest for repeatability is one reason why certification norms are so detailed, as will become quite clear in the following sections of this Chapter. For practical reasons, the number of flyover noise measurements is limited, certainly to an extent that large number statistics cannot be applied. As stated before, 4 to 6 valid test flights is all that is required for any particular noise certification procedure. Appendix B to this AGARDograph is therefore devoted to the problem of statistical accuracy and repeatability in measuring aircraft noise with small sample size.

2.2 ICAO ANNEX 16

The flight test and analysis procedures for aircraft noise-certification have been developed by the 'International Civil Aviation Organisation' (ICAO) within the last two decades. For this purpose, ICAO had instituted a special body, the 'Committee of Aircraft Noise' (CAN), which has been responsible for developing, reviewing and improving the noise certification procedures for all types of aircraft. In the course of time, there have been 7 major CAN-meetings (CAN/1 to CAN/7) every two to three years. In 1983, CAN has been renamed 'Committee on Aviation Environmental Protection' (CAEP) to reflect its broader scope, which now covers all kinds of aircraft emissions (including engine exhaust gases). The first (and most recent) meeting of CAEP ("CAEP/1") occurred in 1986, and this AGARDograph essentially reflects the state of noise certification as of this date, taking however all amendments since that time into account.

Noise-certification "Standards" and "Recommended Practices" (so-called 'SARPs') for subsonic jet-aircraft and heavy propeller-driven aeroplanes were first issued more than 15 years ago. Corresponding SARPs for light propeller-driven aeroplanes were introduced in 1975, and for helicopters in 1981 (Fig. 2.4). Approximately 150 airfaring states presently contract to ICAO. Here, the term "contract" implies that such states in their national noise legislation adhere to ICAO SARPs. No state is forced to accept or adopt these entirely, but any deviation in the application by a national authority must officially be brought to the attention of ICAO. It is worth noting that at present only 10 to 15 of the ICAO member states are represented in, or directly contribute to the work of, CAEP. The ICAO-document, which contains all specifications for controlling aircraft noise emission and immission, is entitled "International Standards and Recommended Practices - Environmental Protection; ANNEX 16 to the Convention on International Civil Aviation / Volume 1 'Aircraft Noise' |1|. Its first edition dates from 1981, its second edition appeared in 1988. This document is commonly referred to as "ANNEX 16".

2.3 Structure and Content of ANNEX 16 (1988 Edition)

There have been several editions of ANNEX 16. The most recent (1988) edition contains, within Volume I, five Parts (with Roman numerals); here Part II , in particular, deals with aircraft noise certification along 10 Chapters, each devoted to a particular type and/or weight-category of aircraft. Furthermore, the ANNEX edition contains six Appendices (with Arabic numerals) and four Attachments (with sequential capital letters). This structure is shown in on Page 10. Of special interest in the context of this AGARDograph are Chapters 3, 6, 8, and 10 of Part II, Appendices 2, 3, 4 and 6, and Attachments A and D, i.e. those dealing with subsonic jet-aeroplanes, heavy and light propeller-driven aeroplanes and helicopters. Understanding the content and structure of ANNEX 16 is helpful, since in the "jargon of the experts" terms such as "Chapter-3 aircraft" or a "Chapter-10 vs a "Chapter-6 procedure" are frequently used.

In ANNEX 16, a CHAPTER defines the noise evaluation measure to be used for the type or category of aircraft (e.g. a 'maximum A-weighted Noise Level' or an 'Effective Perceived Noise Level', etc.), it specifies the measurement locations, the noise limits and certain procedural aspects, such as the required engine-power setting or flight-speed for the certification test. An APPENDIX defines the test environment (e.g. the permissible atmospheric conditions), certain requirements about the data-acquisition equipment and, where necessary, computation procedures for calculating the noise measure. It also contains the requirements for reporting to the authorities. An ATTACHMENT, final-

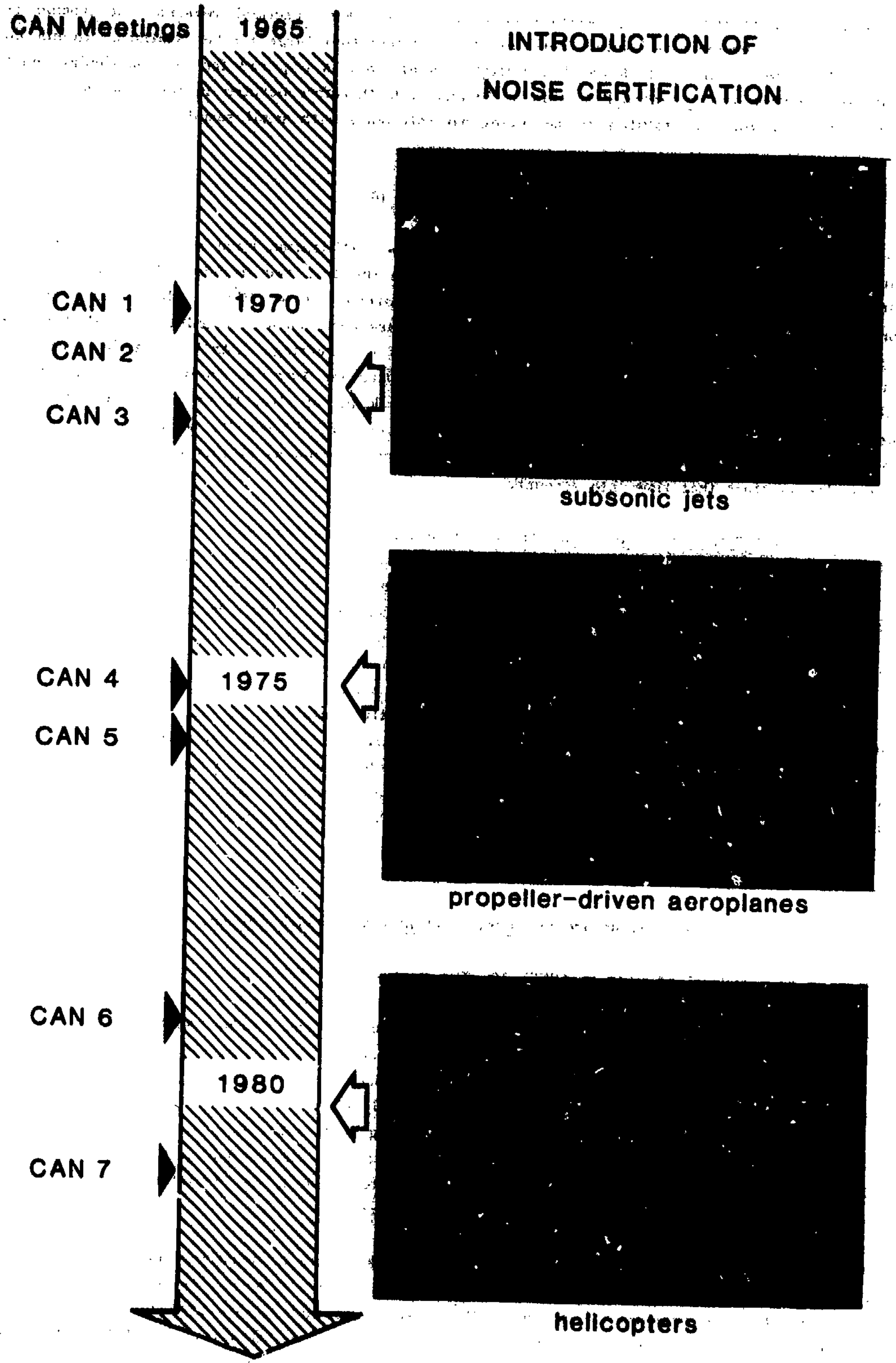


Fig. 2.4 Original schedule for the introduction of aircraft noise certification by the ICAO-'Committee of Aircraft Noise' (CAN) and its successor organization, the ICAO-'Committee on Aviation Environmental Protection' (CAEP)

ly, provides additional guidance material for the application of the rules and regulations of Chapters and Appendices. It may contain simplified mathematical formulations or details of recommended alternate ("equivalent") procedures.

ICAO has generated a special Technical Manual |2| explaining in greater detail the use of the various procedures in the noise certification of aircraft than is possible in the ANNEX 16 document. This Manual must be considered as a very helpful supplement to the ANNEX 16 document per se. As stated in the introduction to this Manual, 'its aim is to promote uniformity in the implementation of the technical procedures of ANNEX 16, Volume 1, and to provide guidance such that all certificating authorities can apply the same degree of stringency and the same criteria for acceptance in approving applications for the use of "equivalent procedures"'. As will be recalled, "equivalent procedures" do not follow exactly the procedures as delineated in ANNEX 16, but provide the same quality data and/or information required for purposes of noise certification; they are usually "more practical" or less involved than the very ANNEX 16 procedures. However, any equivalent procedure must be approved by the certificating authority prior to its application in noise certification.

For purposes of noise certification, propeller-driven aeroplanes have originally been divided, somewhat arbitrarily, into those with a maximum certificated take-off mass of more than 5700 kg, and those not exceeding 5700 kg. This mass limit has recently been raised to 9000 kg. Those below this mass-limit (usually referred to as 'light propeller-driven aeroplanes' or simply LPDA) include the vast majority of General Aviation aeroplanes with one or two engines; those over this limit (usually referred to as 'heavy propeller-driven aeroplanes' or simply HPDA) represent the commercial and/or commuter and heavy transport-category aircraft with 2, 3 or 4 engines and with a mass of up to several hundred-thousand kilograms.

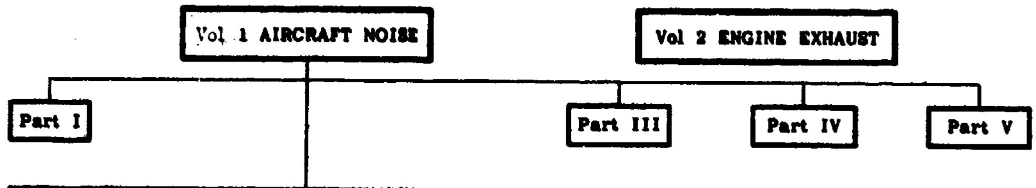
Light propeller aircraft typically operate from smaller airfields, whereas the heavy ones use the same airports as commercial jet-airliners. It was argued, therefore, that the latter should be subjected to the same noise regulations as turbo-jet aeroplanes. Until about 5 years ago, the heavy propeller-driven aeroplanes were dealt with in a separate ANNEX Chapter (Chapter 5), whereas the subsonic jet-aeroplanes were covered in Chapter 2 and in Chapter 3. The latter distinction relates to the date at which the application for the certificate of airworthiness for the prototype was accepted: As shown on the following page, Chapter 2 applies if the application was filed "before 6 October 1977", Chapter 3 if this date was "on or after 6 October 1977". This is in effect a distinction between old and new aircraft. Since the Chapter-2 aeroplanes will be phased out in the Nineties, there is no great need to discuss Chapter 2 in detail.

All new subsonic jet-aeroplanes will have to comply with Chapter 3 regulations (which are more stringent than the Chapter 2 regulations). For the heavy propeller-driven aeroplanes ICAO has inserted an applicability clause into Chapter 3. Those aeroplanes for which the prototype application has been received on or after 17 November 1988 would have to comply with the provisions of Chapter 3. Already in the past, Chapters 3 and 5 utilized one common Appendix, i.e. Appendix 2; the dismissal of Chapter 5 should further consolidate the noise certification of these two types of aircraft.

Subsonic jet aeroplanes and heavy propeller-driven aeroplanes will therefore be discussed jointly in one Section referring to Chapter 3 and - where pertinent - to Chapter 5, not however to Chapter 2; differences between Chapters 3 and 5 will be pointed out.

The noise certification procedure for light propeller-driven aeroplanes is covered in ANNEX 16/ Chapter 6 and Appendix 3. As stated, CAEP/1 raised the mass-distinction between light and heavy propeller-driven aeroplanes to 9000 kg. Chapter 6 now includes aeroplanes up to that mass-value. Recently, ICAO introduced an altogether new noise certification procedure for light propeller-driven aeroplanes. The new procedure defines an entirely different test-methodology. The relevant ANNEX Sections are termed Chapter 10 and Appendix 6. Although the new noise certification procedure became effective as of 17 November 1988, there is a fall-back provision: aeroplanes which are un-able to meet the Chapter-10 specifications may still be noise-certificated after the established Chapter 6 for a number of years. Hence, both Chapter 6/Appendix 2 and Chapter 10/Appendix 6 will be discussed.

Content Structure of ANNEX 16 Second Edition 1988



Part II CHAPTERS: Aircraft Noise Certification	
Chap. 1:	Administration
Chap. 2:	Subsonic Jet Aeroplanes (ACA* before 6 Oct 77)
Chap. 3:	Subsonic Jet Aeroplanes (ACA on/after 6 Oct 77)
	Prop.-driven Aeroplanes over 5700 kg (ACA on/after 1 Jan 85; before 17 Nov 88)
	Prop.-driven Aeroplanes over 9000 kg (ACA on/after 17 Nov 88)
Chap. 4:	Supersonic Aeroplanes
Chap. 5:	Propeller-driven Aeroplanes over 5700 kg (ACA before 1 Jan 85)
Chap. 6:	Propeller-driven Aeroplanes not exceeding 9000 kg (ACA before 17 Nov 88)
Chap. 7:	Propeller-driven STOL Aeroplanes
Chap. 8:	Helicopters
Chap. 9:	Auxiliary Power units and Aircraft Systems at Ground Operation
Chap.10:	Propeller-driven Aeroplanes not exceeding 9000 kg (ACA on/after 17 Nov 88)

APPENDICES: Evaluation of Noise Certification of ...	
App. 1:	Subsonic Jet Aeroplanes (ACA before 6 Oct 77)
App. 2:	Subsonic Jet Aeroplanes (ACA on/after 6 Oct 77)
	Prop.-driven Aeroplanes over 5700 kg (ACA on/after 1 Jan 85; before 17 Nov 88)
	Prop.-driven Aeroplanes over 9000 kg (ACA on/after 17 Nov 88)
App. 3:	Propeller-driven Aeroplanes not exceeding 9000 kg (ACA before 17 Nov 88)
App. 4:	Helicopters
App. 5:	Monitoring Aircraft Noise at Aerodromes
App. 6:	Propeller-driven Aeroplanes not exceeding 9000 kg (ACA on/after 17 Nov 88)

ATTACHMENTS: Guidance and Explanatory Material	
Att. A:	Equations for Noise Level Calculations
Att. B:	Noise Certification of Propeller-driven STOL Aeroplanes
Att. C:	Noise Certification of Auxiliary Power Units (APUs)
Att. D:	Alternative Method for Helicopter Noise Measurement

*) ACA = Airworthiness Certificate Application for the Prototype accepted

The current applicability of certain ANNEX Chapters and Appendices for propeller-driven aeroplanes does, however, not only depend on their mass, but also on the date, when the application for the prototype airworthiness certificate was applied for. Presently, with several Chapters and Appendices being in force simultaneously, the picture - for the "uninitiated" - is somewhat confusing. To help untangle this "applicability snarl", the following listing is provided:

Propeller-driven Aeroplane Noise Certification Applicability Schedule

Aircraft Weight (Mass)	Airworthiness Certificate Application accepted	Applicable Chapter	Applicable Appendix
not exceeding 9000 kg	before 17 Nov. 88	6	3
not exceeding 9000 kg	on or after 17 Nov. 88	10	6
over 5700 kg	before 1 Feb. 85	5	2
over 5700 kg	on or after 1 Jan 85 before 17 Nov 88	3	2
over 9000 kg	on or after 17 Nov. 88	3	2

Helicopter noise certification is covered in the ANNEX in Chapter 8 and Appendix 4 and will be discussed in its latest 'CAEP/1'-version. Although the helicopter noise certification Standards have been in effect for only a few years, several substantial changes have since been implemented.

There are many commonalities in the noise certification procedures between the various types of aircraft. Rather than discussing, however, common features of noise certification for jet aircraft, propeller-driven aircraft and helicopters, and pointing out differences as they arise, it was considered more beneficial for the reader to treat each aircraft category essentially on an individual basis. The reader can then go through the particular chapter for the type of aircraft of his interest, and readily obtain all the necessary information. For ease of reference, however, Appendix C* of this AGARDograph compares noise certification aspects according to aircraft types and categories.

Each major section in the following is therefore devoted to particular types of aircraft: Section 2.4 to subsonic jet aeroplanes and heavy propeller driven aeroplanes; Section 2.5 to light propeller-driven aeroplanes, current procedure; Section 2.6 to light propeller-driven aeroplanes, new procedure; and Section 2.7 to helicopters.

* The reader will realise that the author faces a slight dilemma: This AGARDograph has chapters and appendices, so has the ANNEX 16. From the context it should however become clear what is meant. To somewhat reduce a possible confusion, AGARDograph-Appendices will be identified by capital letters A, B, C, etc, rather than by numbers, as in the ANNEX.

2.4 Noise Certification of Subsonic Jet Aeroplanes and Heavy Propeller-driven Aeroplanes (ANNEX 16: Chapters 3 and 5, and Appendix 2)

2.4.1 Applicability

Chapter 3 and Appendix 2 of ANNEX 16 are thus applicable (1) to subsonic jet aeroplanes with prototype airworthiness application accepted on or after 6 October 1977, (2) to propeller-driven aeroplanes over 8700 kg with prototype airworthiness application accepted on or after 1 January 1985 and before 17 November 1988, and (3) for propeller-driven aeroplanes over 9000 kg with prototype airworthiness application accepted on or after 17 November 1988.

Chapter 3 also covers derived versions of subsonic jet-aeroplanes. A 'derived version', in ICAO's definition, is an aircraft, which from the point of airworthiness is similar to the prototype, but incorporates changes in type design which may affect its noise characteristics. Such changes could pertain to an increased take-off weight or engine thrust, or to modifications of the power-plant. If only minor changes are made, it is often possible to derive the certification levels from those of the original aircraft either analytically or by means of a less extensive, supplemental, flight test program. If changes are significant from a noise point of view, then the entire noise certification procedure would have to be executed.

A discussion on utilizing "datum aircraft" noise data to extrapolate towards noise certification levels of derived aircraft, using "noise/power/distance"-charts appears in Section 4.2 of this AGARDograph.

2.4.2 Reference Noise Measurement Points and Flight Procedures

The aircraft to be noise-tested must perform a number of regular take-offs and landing approaches. For the take-offs noise must be measured directly below the flight path and along a sideline, for landing approaches only below the flight-path. Figs. 2.5a and 2.5b specify the reference noise measurement points (i.e. the points where, ideally, the measuring microphones should be positioned) and the reference flight paths to be followed. During flight tests it will not usually be possible to fly exactly by the "reference" trajectory and the environmental conditions will not exactly be those specified in the certification requirements. It may also be impossible to position the microphones at the exact reference positions. Thus, one must distinguish between "reference"-conditions and "measurement"-conditions. In fact, substantial effort is required in noise certification to correct or adjust data from measurement to reference, as will be discussed in the appropriate sections of this AGARDograph.

(a) Take-off

A jet aeroplane must employ average* take-off thrust until a certain minimum height above the runway is reached. This specified height depends on the number of engines (2 engines - 300 m, 3 engines - 260 m, 4 or more engines - 210 m). Thereafter, thrust may be reduced to a value which will either allow to maintain at least a 4%-climb-gradient or to maintain level flight with one engine out. The greater of these two thrust-settings must be used. Since in the second case all engines will be operating during the flight test, the aircraft will then still climb. These requirements precisely define the take-off reference flight path. During this take-off test, jet aeroplanes must maintain a flight-speed between V_2 + 19 km/h and V_2 + 37 km/h, where V_2 is the "safe take-off speed".

In the certification requirements for propeller-driven aeroplanes the take-off reference flight path is defined by the application of take-off power (rather than thrust) until the engine-number-related

* the term "average" refers to the mean characteristics of the production engine

flight height is reached and the subsequent reduction in engine power has occurred for the same climb-gradient and level-flight specifications, respectively, as for jet aeroplanes. In the case of propeller-driven aeroplanes only the minimum climb speed of V_2 + 19 km/h is specified.

Both types of aircraft must maintain a constant take-off configuration (in essence a constant flap-setting) during the entire test-flight. The landing gears may be retracted as soon as practical after actual take-off. At least one of the test flights must be conducted with maximum take-off mass, while other flights may be conducted with less mass, depending on the continuing depletion of the fuel tanks. Weight in this context is not considered a very noise-relevant parameter.

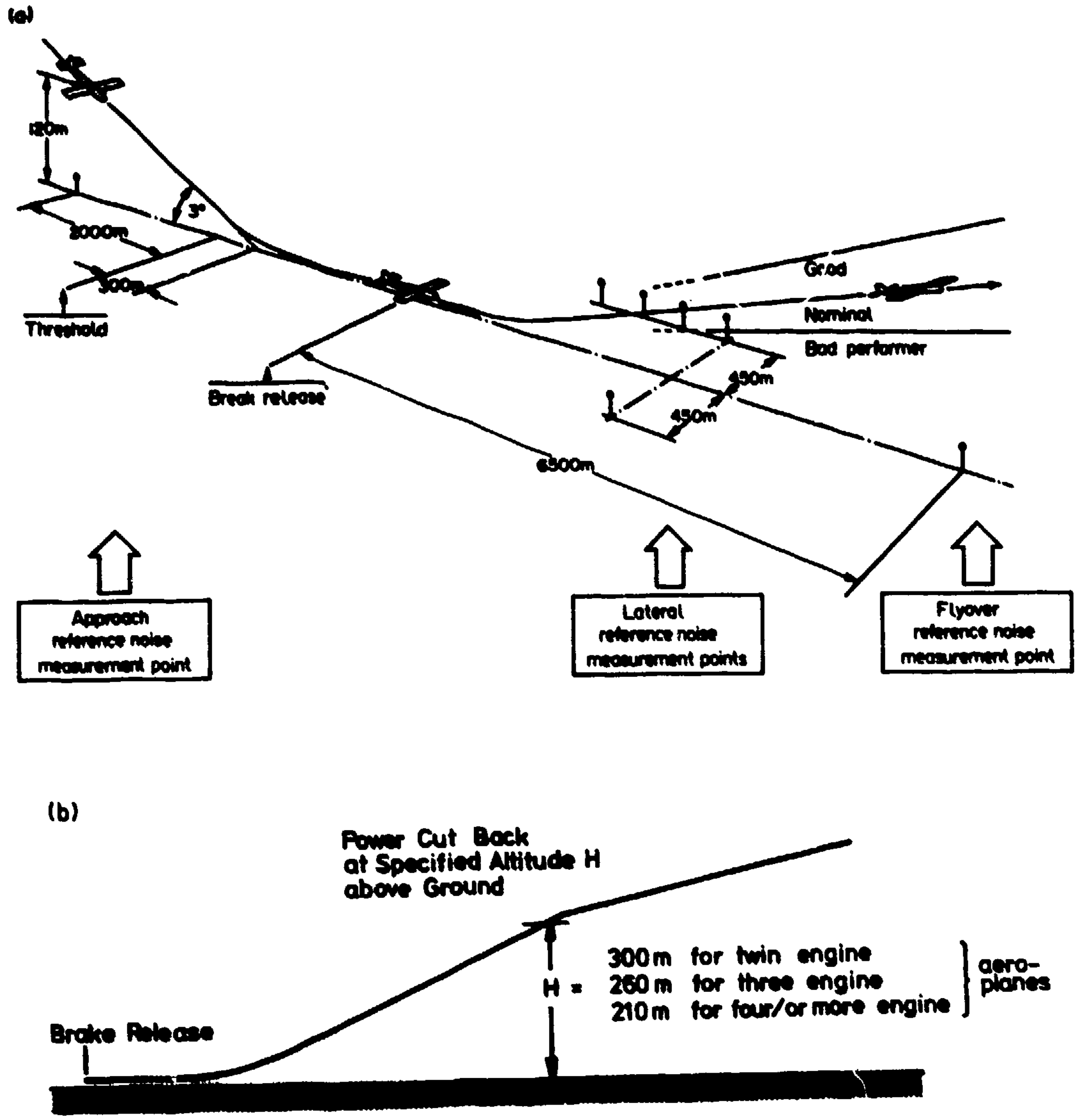


Fig. 2.5 Reference noise measurement points and reference flight procedure for heavy propeller-driven aeroplanes and subsonic jet-aircraft:

(a) Approach noise measurement point and take-off measurement point (flyover/lateral)
(b) Power cut-back option during take-off

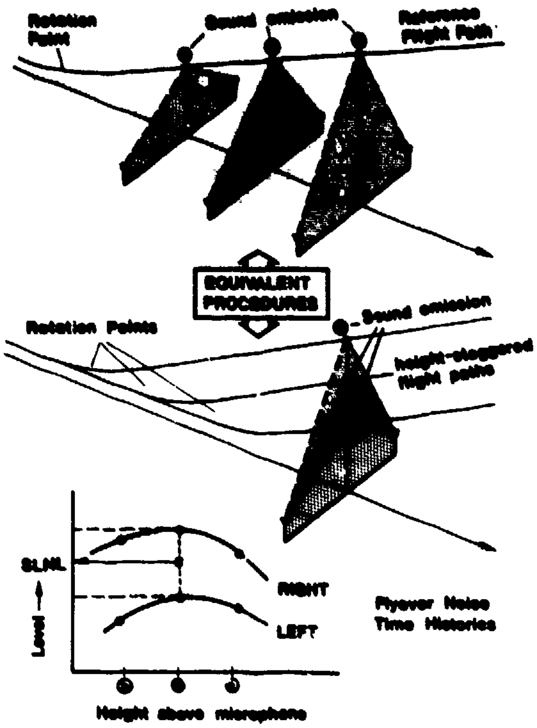


Fig. 2.6 Equivalent procedure to determine side-line noise levels with two microphones only (rather than with a lateral array of several microphones)

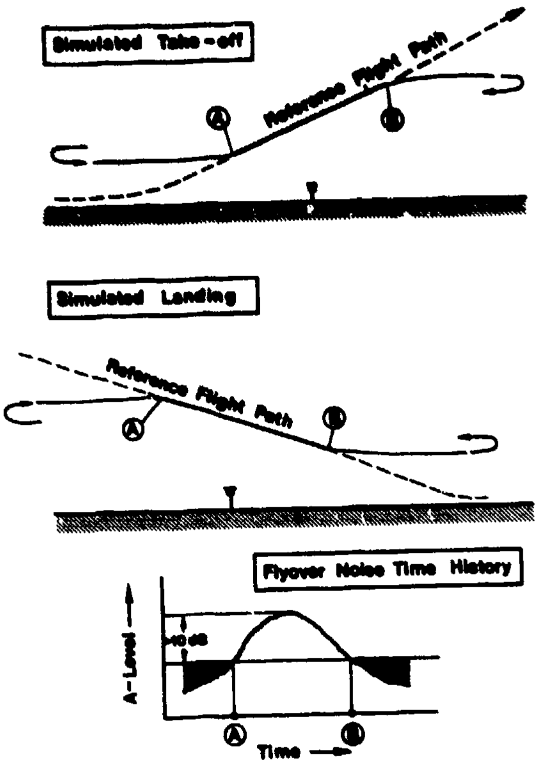
For the take-off procedure, two reference measurement-"points" are defined: one such point, the flyover reference noise measurement point is located on the extended runway centerline 6500 m from brake-release. The other point, the lateral, or side-line reference noise measurement point, is located on a line parallel to and 450 m to the left or right side of the runway-centerline. Since the longitudinal position of this point is not known prior to the test a sufficiently extended and appropriately spaced array of microphones must be positioned along the side-line to ensure that the maximum level is caught. To prove symmetry of the noise-signature on both sides, at least one additional microphone must be positioned at a corresponding location on the other side. Obviously, lateral noise-data acquisition requires much equipment and subsequent data-processing. To reduce the effort, an equivalent method has been worked out by ICAO, proposed as an alternative test procedure (if individually approved by the certificating authorities under the prevailing test conditions). This method basically requires only two laterally positioned microphones, as illustrated in Fig. 2.6. Repeated take-off flights with different rotation points will bring the aircraft at different heights above the connecting line between the microphones. Each time, the radiation angle from the aircraft to the microphones will be different, resulting in different - height-dependent - noise levels at the microphones. By taking the average level between the two microphones, a maximum "side line noise level" can then be derived. The maximum side line noise level must be determined for the aircraft taking off with maximum thrust or power, maintaining this maximum engine setting for the entire side-line noise test. No power cut-back is permitted.

An aeroplane with good performance climbs faster than one with poor performance and will thus be farther from the lateral and the flyover reference points by the time the maximum flyby or flyover noise levels are recorded. Greater distance, generally, means more attenuation and, hence, performance enters directly into the measured noise-level.

For the take-off test, the aeroplane must not necessarily conduct an actual take off from some brake-release point. Employing again an "equivalent procedure" the aeroplane can rather intercept the take-off reference flight path at a point, where the radiated noise is well below the relevant maximum noise level (how much below, will be discussed later in the section on the noise evaluation measures). This "equivalent procedure" is illustrated in Fig. 2.7.

(b) Approach

For the approach noise test, the aircraft - in its landing configuration (flaps and landing gear down) - follows a 3-degree glide path until touch down. The approach reference noise measurement point is located 2000 m before the threshold. As the glide path antenna is positioned 300 m inside the threshold along the runway this in effect corresponds to a height of 120 m for a 3-degree



Ⓐ Point in Time before which Reference-climb-path ("Take-off") or Reference-approach-path ("Landing") must be intercepted

Ⓑ Point in Time after which Reference-flight-paths may be left

Fig. 2.7 Equivalent procedure for approach intercept and take-off intercept to avoid actual touch-down or start from brake-release point

descent path. This path is designated the approach reference flight path. The approach speed must not be less than 1.3 V_s + 19 km/h, where V_s is the stalling speed, and at least one test flight - out of the minimum required number - must be conducted with the <u>maximum landing mass</u>.

Employing again an equivalent procedure, the test can be conducted without an actual touch-down. In this case, the aeroplane intercepts the approach reference flight path at a point, where the noise is well below the maximum and follows that path beyond the reference noise measurement point until the radiated noise has dropped sufficiently below the maximum; now, the aircraft may leave the reference flight path to turn around for another approach flight test (see Fig. 2.7).

As the test regulations specify the approach flight test to be conducted for the "most critical" (i.e. noisiest!) condition, a number of pre-check flights are necessary with different flap-setting (at the specified or stabilized air speed) to determine that particular most critical configuration. Only after that configuration has been established, the required minimum number of test flights necessary to obtain the average noise level (see Section 2.4.7.d) can be executed.

2.4.3 <u>Noise Evaluation Measure and Noise Limits</u>

The noise evaluation measure for both heavy propeller-driven aeroplanes and subsonic jet aeroplanes is the 'Effective Perceived Noise Level (EPNL)'. The maximum permissible EPNL-values at the three reference-noise measurement points, when obtained in accordance with the reference flight procedures, are shown in <u>Fig. 2.8a</u> for heavy propeller-driven aeroplanes according to (the outdated) Chapter 5, and in <u>Fig. 2.8b</u> for subsonic jet aeroplanes and heavy propeller-driven aeroplanes according to Chapter 3. The EPNL-limits are related to the aircraft's maximum certificated take-off mass or landing mass, respectively. The Chapter 3 noise limits for the flyover test differ with the number of engines of the aircraft; no such distinction had been used in Chapter 5. Also, Chapter 5 noise limits were somewhat less stringent than Chapter 3 limits.

Noise-limits are constant for the lower values of aircraft mass. Beyond a first "break-point" the noise limits vary at different rates with the <u>logarithm</u> of the mass up to a second "break-point", beyond which the limits are again constant and mass-independent. For convenience, the noise limits in EPNdB and the two break-points are listed below in <u>TABLE 1</u> for Chapter 5 aeroplanes, and in <u>TABLE 2</u> for Chapter 3 aeroplanes:

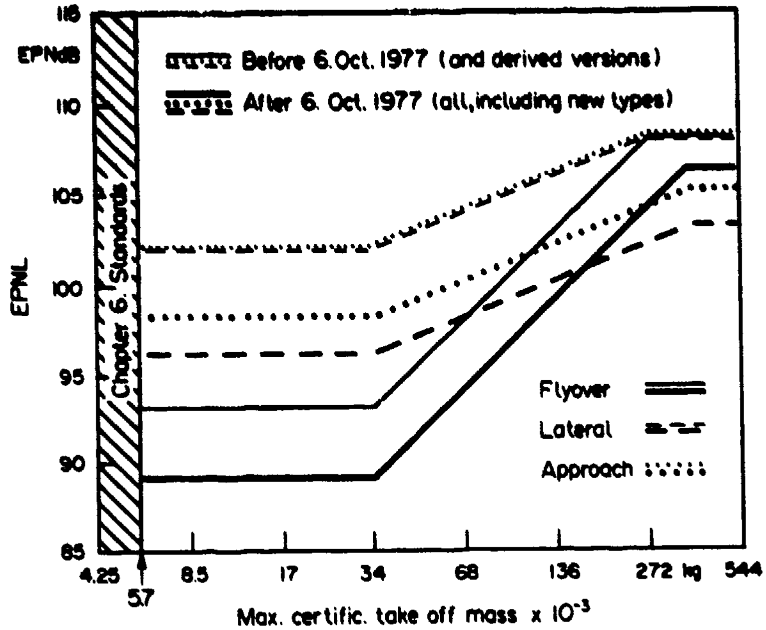


Fig. 2.8a

EPNL-limit as function of the maximum certificated take-off mass for "heavy" propeller driven aeroplanes over 5700 kg take-off mass after ANNEX 16, Chapter 5

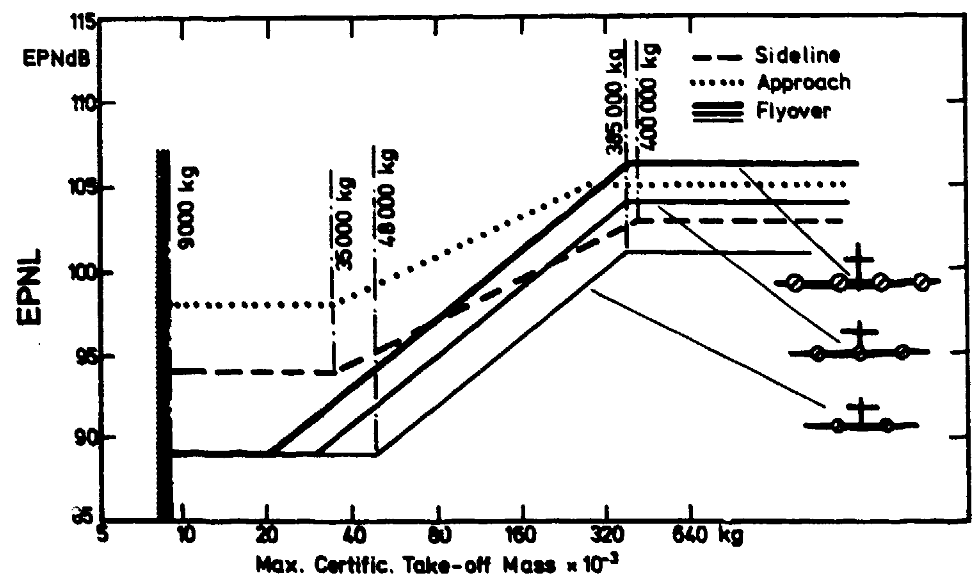


Fig. 2.8b EPNL-limit as function of the maximum certificated take-off mass for subsonic jet-aircraft and "heavy" propeller driven aeroplanes over 9000 kg take off mass after ANNEX 16, Chapter 3

TABLE 1 Chapter-5 noise limits for heavy propeller-driven aeroplanes (until the applicability date of Chapter-3 for these aeroplanes)

Flyover Noise Limit:	89 EPNdB up to 34.000 kg;	106 EPNdB above 388.900 kg
Approach Noise Limit:	98 EPNdB up to 34.000 kg;	108 EPNdB above 384.700 kg
Lateral Noise Limit:	96 EPNdB up to 34.000 kg;	103 EPNdB above 384.700 kg

TABLE 2 Chapter-3 noise limits for heavy propeller-driven aeroplanes <u>and</u> subsonic jet-aircraft

Flyover Noise Limit:		
- 1 or 2 engines	89 EPNdB up to 48.100 kg;	101 EPNdB above 385.000 kg
- 3 engines	89 EPNdB up to 28.600 kg;	104 EPNdB above 385.000 kg
- 4 engines	89 EPNdB up to 20.200 kg;	106 EPNdB above 385.000 kg
Approach Noise Limit:	98 EPNdB up to 35.000 kg;	105 EPNdB above 280.000 kg
Lateral Noise Limit:	94 EPNdB up to 35.000 kg;	103 EPNdB above 400.000 kg

2.4.4 <u>Reference and Permissible Test Atmospheric Conditions</u>

Reference atmospheric conditions have been defined as follows

- o sea-level atmospheric pressure of 1013.25 hPa;
- o ambient air temperature of 25 °C (i.e. ISA + 10°C);
- o relative humidity of 70 %;
- o zero wind.

(At the discretion of the certificating authorities a 15 °C Reference Temperature may be used. However in this case 1 EPNdB must be added to the measured flyover noise level)

Such conditions, in that particular combination, are unlikely to occur simultaneously. In order to enable measurements outside these reference conditions, certain <u>test-windows</u> have been defined and procedures have been developed to correct noise data to the reference atmospheric conditions. The following test windows were established:

- o ambient air temperature (T) along the entire noise propagation path must not be below 2 °C or above 35 °C;
- o relative humidity (RH) along the entire noise propagation path must not be below 20 % or above 95 %;
- o certain combinations of RH and T that would result in an atmospheric sound attenuation in excess of 12 dB/100 m in the 8-kHz-1/3-octave-band must be avoided* (<u>Fig. 2.9</u> shows the permissible RH/T-window);
- o the average wind must not exceed 22 km/h and the cross-wind component (relative to the flight direction) must not exceed 13 km/h.

The above atmospheric conditions should prevail over the whole noise path between the aircraft and 10 m above ground. This specification emphasizes the need to acquire temperature and humidity profiles within this height range and preferably beyond to ascertain the absence of a temperature inversion which would prohibit noise certification testing. There are even more detailed specifications in Appendix 2 about the atmospheric noise attenuation should the prevailing atmospheric

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* the sound attenuation coefficient is a function of frequency, relative humidity and temperature. Its value, expressed in terms of dB/100 m is available from Tables |3a, 3b| and <u>Appendix D</u>

conditions make it necessary to calculate the absorption in "layered altitude sections". Whether such a "layered calculation" is actually required depends on the change of the attenuation coefficient in the 3.2 kHz third-octave band: if this coefficient varies by more than 0.5 dB per 100 m anywhere along the noise propagation path between aircraft and 10 m above ground, the layering must be taken into account; this is done by adding the effective 'attenuation per layer' to arrive at the composite attenuation for the whole noise path.

The wind speed data - measured 10 m above ground - must be averaged over 30 second periods; during this period short-duration gusts of up to 28 km/h are permissible. Furthermore - and stated rather vaguely - no "anomalous" wind conditions should exist that could significantly affect the recorded noise level at any of the measurement points.

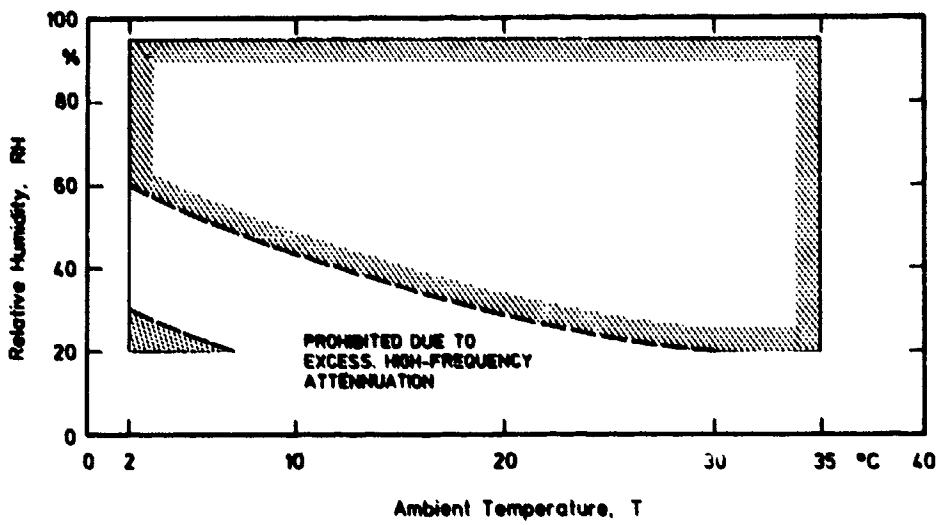

Fig. 2.9 Area of permitted combination of Relative Humidity (RH) and air Temperature (T) for noise certification testing of "heavy" propeller driven aeroplanes above 5700 kg take-off mass and subsonic jet aircraft after ANNEX 16, Chapter 3

2.4.5 Flight-Path Tracking

Since the measured acoustic data must be corrected to reference conditions, precise information on the actual flight path is also necessary. The flight path will in all likelihood differ from the reference flight path, both in height and lateral displacement. Thus accurate tracking is required, preferably by some aircraft-independent means, such as radar-, laser- or other photographic methods. Tracking methods and equipment are discussed in Section 3.3.1 of this AGARDograph. To relate the noise signature to the aeroplane position, precise time synchronization between the aircraft trajectory and the noise measurements must also be established.

2.4.6 Acoustic Data Acquisition

The microphones must be 1.2 m above the ground surface, a height that is notorious for inducing grave measuring errors on account of the superposition of the directly incident and the ground-reflected acoustic wave; associated problems are discussed in detail in Section 4.3.3. The microphone should be of the pressure type. Data acquisition instrumentation in general, and microphone types in particular are discussed in Section 3.2 of this AGARDograph.

A pressure-type microphone (rather than a free-field type microphone) offers an important advantage: if the microphone diaphragm is oriented for grazing sound incidence (i.e. the wave fronts of the sound approach the microphone under 90 degrees with respect to the microphone axis), a pressure-type microphone's sensitivity is independent of the sound immission angle. Since sound radiated from an aircraft in flyover continuously changes its azimuthal angle with respect to the measuring point no pronounced change in directivity-response for the aircraft approaching or receeding should thus occur. The "grazing-incidence" condition is somewhat difficult to realize for the lateral microphone(s), since sound incidence direction changes in yet another plane. A more detailed discussion of microphone characteristics appears in Section 3.2.1.

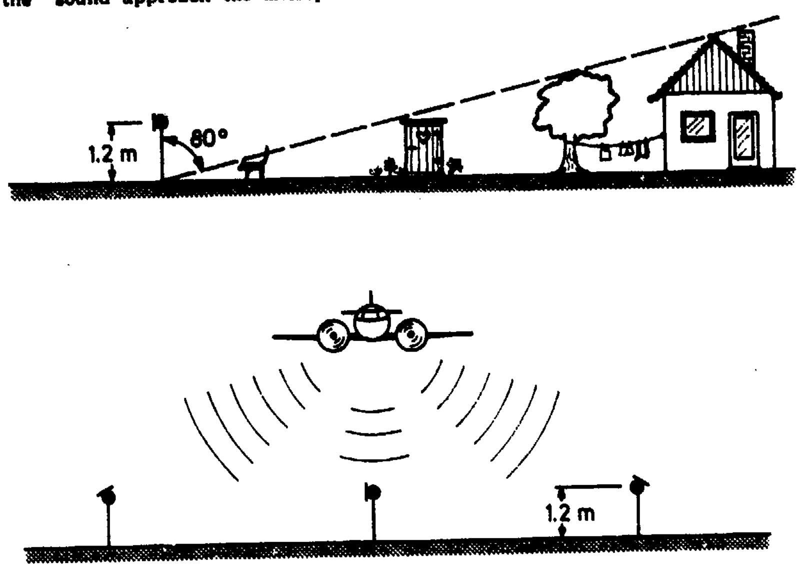

Fig. 2.10 Boundary conditions for noise certification testing of heavy propeller-driven aeroplanes and subsonic jet-aircraft; top: microphone height above ground and reflection-free vertical cone; bottom: grazing incidence diaphragm condition

The area around the microphone must be free from obstructions within a cone of 80° from the vertical to avoid reflections from nearby surfaces. The microphones must meet certain specifications as to their frequency response (which must lie within +/- 1 dB from 45 Hz to 4.5 kHz); also, their sensitivity should change no more than 2.5 dB within a 30°-variation from the grazing incidence reference direction, again for the same frequency range. Use of a wind-screen ("wind-ball") is recommended. Fig. 2.10 illustrates some of these requirements.

High standards are also set for the quality of the data recording and analysis systems, and appropriate calibration signals must be recorded; furthermore both the acoustic and the electronic background noise must be determined in the absence of test-object noise. A detailed discussion of recording and analysis equipment specifications and their use appears in Chapter 3.2 of this AGARDograph.

2.4.7 Data Adjustment

Acoustic data measured under conditions that differ from the reference conditions (e.g in regard of the flight path, the meteorological environment, the aircraft operational parameters or the noise measurement points) must be corrected to reference conditions to permit their evaluation against the noise limits. Three correction terms, Delta 1, Delta 2, and Delta 3 must be determined and added to the EPNL-value as obtained from the measurements.

Delta 1 accounts for (a) the atmospheric attenuation due to differences from the reference temperature and humidity, (b) the atmospheric attenuation due to the change in effective slant range, and

(c) the "inverse square" distance attenuation due to the change in effective slant range. Delta 2 accounts for the duration ("10-dB-down-time")* of the noise as affected by the distance and speed of the aeroplane relative to the measurement point. Delta 3 is in effect a source noise correction, accounting for the influence of environmental parameters (such as temperature, ambient pressure) on the noise output of the source itself.

The basic considerations for establishing the correction terms Delta 1 to Delta 3 are discussed in the following:

(a) Correction for Noise Received on the Ground (Delta 1 and Delta 2 terms)

If the flight-path differs from the reference path, the distance of the aircraft to the measuring microphone will also differ from that under reference conditions. A change in acoustic path length affects, however, both the amount of atmospheric absorption and the spherical spreading attenuation (inverse square distance attenuation). In computing the EPNL of a flyover noise event, each successive 1/3-octave band spectrum at the 0.5 second time increments should individually be corrected for these attenuations, in correspondence with the prevailing - perhaps layered - atmospheric conditions (temperature and humidity) and the distance from the microphone at the time, before conversion of the measured acoustic data into a PNL-value; this latter requirement emphasizes the need to synchronise acoustic and flight path information.

Which distance, then, must be used in this correction? If the aircraft would be flying exactly on the reference flight path there would be one particular instant in time and one particular aircraft position, where that signal was emitted which on the ground resulted in the maximum tone-corrected 'Perceived Noise Level, PNLTM'. That position defines a particular distance between aeroplane and measurement point, termed the "reference-distance". If, however, the actual flight path differs from the reference flight path, this position and the effective distance "aeroplane/measurement-point" are different. Hence the actual attenuations (due to atmospheric absorption and spherical spreading) must be converted to "reference attenuations" to correct flight data to reference conditions.

A "simplified" correction method has been developed, which is based on the following reasoning: While flying on the measurement flight path, the "sound-ray" that caused PNLTM to occur at the measurement point has a certain angle with respect to the flight path. It is now assumed that this angle is characteristic for the occurrence of the PNLTM at the measurement point, even if the angle between flight-path and ground-surface was actually different. Thus, as illustrated in Fig. 2.11 the difference in measurement-distance QK and reference-distance Q_rK_r can be determined, and used in the subsequent corrections. Similar considerations apply when the distance to the lateral measurement point differs from the reference point.

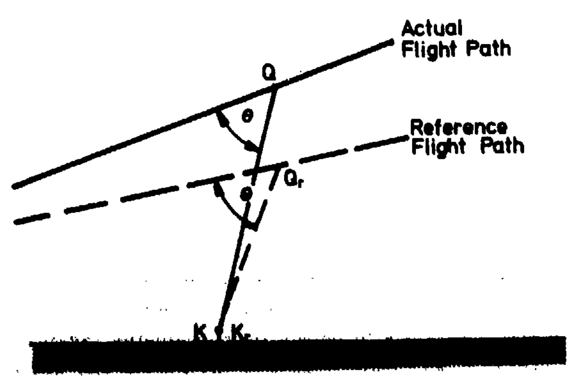

Fig. 2.11 Determination of reference distance 'aeroplane/noise-measurement-point' from measured distance (for source to ground correction) for cases 'flyover' and 'approach'

From the several dozens of 1/3-octave-band spectra measured at 0.5-second increments that particular 1/3-octave band spectrum is selected which was "responsible" for generating PNLTM on the ground. Each of its individual 1/3-octave-band levels are corrected for atmospheric attenuation and the entire spectrum for the "inverse square distance law"-attenuation (which is frequency-independent). The following example for a flyover measurement point illustrates the procedure:

* The term and relevance of the 10-dB-down-time is explained in Appendix A to this Agardograph.

Let us assume that measurement temperature and humidity, respectively, had been 15 °C and 50 % (vs. the reference-conditions of 25 °C and 70 %), and that, furthermore, the measurement distance QK had been 600 m (vs. a reference distance of, say, Q_rK_r = 540 m). The 1/3-octave-band to be considered was 5000 Hz. From appropriate Tables that list the atmospheric sound attenunation-c efficients α in dB/100 m (see APPENDIX D to this AGARDograph) the following data are obtained.

Measurement Condition: $\alpha_{5000\ Hz}$ (for 15°/50%) = 4.2 dB/100 m

Reference Condition: $\alpha_{5000\ Hz}$ (for 25°/70%) = 2.9 dB/100 m

Accordingly

$+ 0.01\ (\alpha_{meas} - \alpha_{ref})\ QK$	=	7.8 dB (atmospheric attenuation due to difference in temperature and humidity)
$+ 0.01\ \alpha_{ref}\ (QK - Q_rK_r)$	=	1.7 dB (atmospheric attenuation due to distance change)
$+ 20 \log (QK/Q_rK_r)$	=	0.9 dB (inverse square distance attenuation)

Thus, the total correction to the measured level in the 5000 Hz band would be +10.4 dB. In a similar manner all the other 1/3-octave band levels of the remainder of the (one only!) spectrum is corrected and converted into a $PNLT_{ref}$. From that, the correction term 'Delta 1' is determined as

$$\text{Delta 1} = PNLT_{ref} - PNLTM_{meas}$$

and added to the EPNL-value.

Since the 10-dB-down-time is both a function of distance and ground velocity (≙ flight velocity relative to the ground) an adjustment to the duration correction is required, when reference and measurement distances and/or ground velocities differ. This correction, Delta 2, is computed as follows

$$\text{Delta 2} = -10 \log (QK/Q_rK_r) + 10 \log (V/V_r)$$

and also added to the measured EPNL-value.

The third correction term Delta 3 will now be discussed in the context of the source noise correction:

(b) Source-Noise Correction - Jet Engine Noise (Delta 3 term)

While the previously discussed corrections Delta 1 and Delta 2 accounted for measurement-to-reference differences in distance and atmospheric conditions, i.e. parameters that affect the noise after it has left the aeroplane, the source noise at the aircraft itself is also affected by environmental parameters. The thrust of a jet-engine, for example, is influenced by temperature and ambient pressure and also by air speed. Differences between the thrust at the measurement conditions and those at reference conditions must therefore be accounted for.

An aircraft propelled by a turbo-jet or a fan-jet engine is, however, by no means a point-source with a well defined directivity. Rather does the primary source on a subsonic jet aircraft, i.e. the engine itself consists of at least 2 individual "subsources", namely the fan and the jet, both of which differ grossly in terms of their acoustic characteristics. Fig. 2.12 shows a (rather well-known) representation where the typical directivity of a modern fan-jet engine specifically that of the fan and that of the jet, is illustrated. Moreover, the fan spectrum usually contains harmonic sound components, while the jet spectrum is of broadband nature. The fan maximum is directed forward/downward while the jet maximum is in the rear directivity arc. Hence in considering a fan-jet engine propelled aircraft in flyover one should realise that it is really a fan and a jet that fly over the observer. Therefore these two should be considered on an individual basis and corrections be applied accordingly.

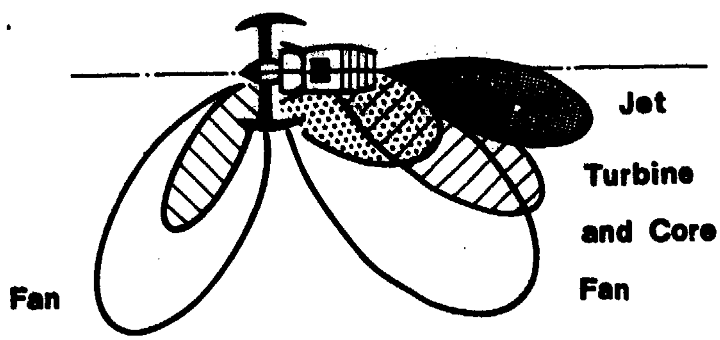

Fig. 2.12 Noise directivity of source components for a turbofan/jet-engine

The noise affecting parameter μ could thus be predominantly related to the fan or to the jet. As it is difficult to clearly separate one from the other, one could argue that for a high bypass ratio engine (BPR around 5) it is the fan whose noise dominates; one should thus base any correction-procedure on the engine's "noise versus fan-speed" behavior.

Alternatively, for a low bypass ratio engine (BPR around 1) one should base the correction procedure on the engine's "noise versus thrust"-behavior. Thrust cannot be measured directly in flight; one can however infer the thrust from the readily measurable quantities 'fan-/or compressor rotational speed', 'engine pressure ratio' and 'temperature rise'. The necessary correction Delta 3 can be determined from flight tests, where the dependence of EPNL on the appropriate engine parameter, μ, is established, as schematically illustrated in Fig. 2.13. Such a parameter μ could be the thrust, for example. During a flight test, μ must be varied about the operational conditions applicable to take-off, lateral or approach flight. Delta 3 can then be determined by subtracting the EPNL-value corresponding to the parameter μ at the measurement conditions from the EPNL-value corresponding to μ at reference condition. Delta 3 is added to the measured EPNL-value.

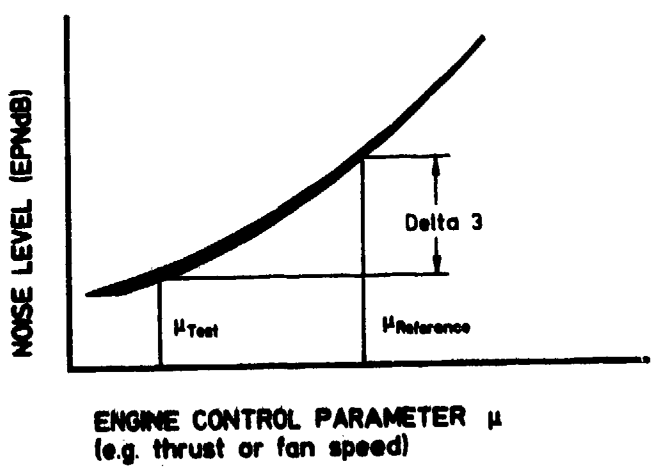

Fig. 2.13 Schematic of noise/thrust or noise/fan-speed relationship for source-noise correction of subsonic jet-aircraft

(c) Source Noise Correction - Propeller Noise (Delta 3 term)

A corresponding Delta 3 correction must also be applied for propeller-driven aeroplanes. Propeller source noise is affected by (1) engine power and (2) blade tip Mach number. Unfortunately, no well founded theoretical or reliable empirical method is available for such a correction. As far as engine power P is concerned, a (K_1 log P_{ref}/P_{meas})-source-noise-adjustment is employed, with K_1 assuming values between 10 and 17. Manufacturer-information on the dependence of engine power on temperature and atmospheric pressure can be utilised to obtain the relevant factor K_1. The error in choosing a slightly "wrong" K-log-power-ratio has, however and fortunately, little effect on the noise level. The value of Delta 3_1 = (K_1 log P_{ref}/P_{meas}) is added to the measured EPNL-value.

Propeller-noise, on the other hand, very much depends on the blade tip Mach number (more precisely on the helical blade tip Mach number 'HTM', which also depends on the forward flight speed). Since Mach-number is a function of temperature, even relatively small differences between test temperature and reference temperature are likely to have a pronounced effect on the propeller noise level, especially if the HTM is high (above approximately 0.8).

ANNEX 16/Appendix 2 recommends to determine the change in source noise level experimentally through ad hoc flight-testing. Additional flight tests could be made at various temperatures, as they occur during the day, and extrapolated towards the reference (temperature) conditions. Alternatively, one might attempt to change the helical blade tip Mach-number by altering the propeller-RPM. It is, however, somewhat questionable whether a Mach-number change through an RPM-change has the same effect on noise as one through a temperature change. Recent wind-tunnel tests (which are discussed in Section 4.6 of this AGARDograph), however, seem to lend support such an approach.

It should be realized, however, that by changing the propeller rotational speed one also changes the fundamental and the harmonic frequencies of the propeller noise spectrum. When using a microphone 1.2 m above ground any one, or several of these frequencies may fall into a cancellation dip. Thus, such tests must be performed with a ground microphone!

It must further be kept in mind that the "check-flights" for each new condition will have to be repeated several times to ensure some statistical validity, making the entire procedure very time consuming. The term to be added to the measured EPNL now is Delta 3_2 = K_2 log HTM_{ref}/HTM_{meas} in dB. K_2 may typically take values of 150 dB or more. The final Delta 3 term for propeller source noise correction thus contains both an engine-power and an HTM related term.

(d) Validity of Test Results

For each of the 3 reference measurement points the arithmetic average EPNL-value must be produced, based on at least 6 valid flights. The sample size, however, must in any case be large enough to establish a confidence limit not to exceed +/- 1.5 EPNdB at a 90% confidence-level. Appendix E to this AGARDograph outlines the relevant procedure and the statistical background in detail.

(e) Trade-offs

Having thus determined and established the required validity of the final EPNL-values for the three reference measurement points, these values are then assessed against the noise-limits. If one, or at most two, of these values exceed the noise limits, then certain "trade-off"-regulations may be applied according to the following rules:

- o the sum of the excesses shall not be greater than 3 EPNdB;
- o the excess at any single point shall not be greater than 2 EPNdB;
- o any excesses shall be offset by reductions at the remaining point(s)

Fig. 2.14 illustrates possible trade-off cases.

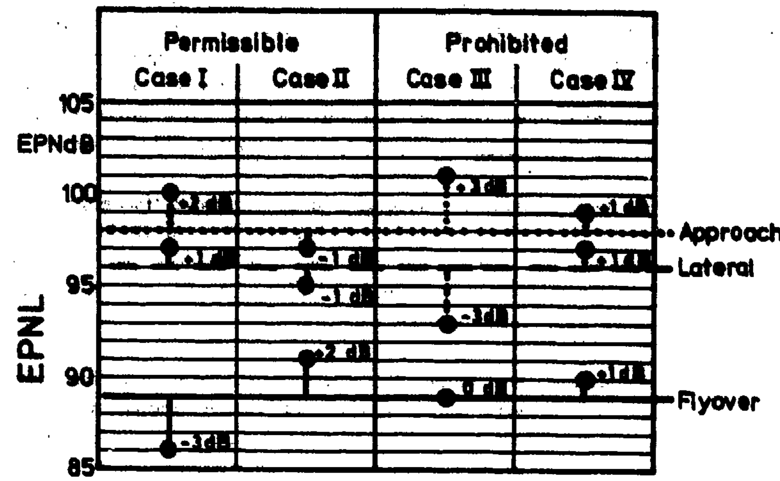

Fig. 2.14

Trade-off possibilities for excess noise levels in the noise certification of propeller-driven aeroplanes over 5700 kg take-off mass and all subsonic jet-aircraft

2.5 Noise Certification of Light Propeller-driven Aeroplanes: Established Procedure (ANNEX 16: Chapter 6 and Appendix 3)

2.5.1 Applicability

Until CAEP/1 in 1986, Chapter 6 and Appendix 3 of ANNEX 16 were applicable to propeller-driven aeroplanes (except special purpose aircraft, such as those for fire-fighting, aerobatics or agricultural applications) with a maximum certificated take-off mass not exceeding 5700 kg. If the prototype of such an aeroplane had been noise-certificated at such a mass, then a derived version with a maximum take-off mass up to 6500 kg could still be certificated under the Chapter 6 specifications.

It was however recognised that there was an emerging commuter category of turboprop aeroplanes with take-off masses in the range of 5700 kg to 15000 kg, for which the Chapter 3 certification procedures are more complex and costly than necessary. It was therefore decided to recommend an extension in the applicability of Chapter 6/Appendix 3 to aeroplane-masses of up to 9000 kg, provided the application for the airworthiness certificate was accepted before 17 November 1988 (for a later application date ANNEX 16/Chapter 10 applies).

2.5.2 Reference Noise Measurement Point and Flight Procedure

For certification test flights, the aeroplane must execute a straight level flight at a height of 300 m +10m/-30m above the acoustic measurement station (reference noise measurement point), with a lateral displacement of not more than 10° from the vertical (corresponding to approximately a 50 m lateral displacement at the 300 m height).

Originally, aircraft engine-power was to be set at maximum continuous power (MCP), a power that is however not normally used in level flight. Therefore, the most recent edition of ANNEX 16 specifies the "highest power in the normal operating range", also termed "maximum normal operating power, MNOP, to be used. It was argued that MCP was not representative for low level circuit flights (which by the proponents of this new regulation were considered to be the acoustically most disturbing) and would only be used for take off and then reduced to about 75 % after cruise altitude had been reached. On the engine tachometer, MPC corresponds to the "end of the green line" which, for a light aircraft, may be around 2700 RPM. MNOP then necessarily corresponds to a lower RPM with accordingly less propeller-generated noise.

Since the noise limits (see subsequent section) were not simultaneously made more stringent, this change in engine-power setting in effect resulted in a relaxation of the noise limits. In the new Chapter-10 noise certification test procedure the issue of the engine power during certification testing is of no consequence.

2.5.3 Noise Evaluation Measure and Noise Limit

The noise evaluation measure is the maximum A-weighted noise level $L_{pA,max}$ occurring during fly-over; this level can be determined - rather simply, and in the field - from visually reading a precision sound-level-meter set at "slow response" (corresponding to the instrument's detector time-constant of 1000 ms). The importance of instrument detector time constant in noise measurements is discussed in Section 3.2.4. Since other acoustic data, such as background noise must also be determined, data are normally recorded and evaluated in the laboratory.

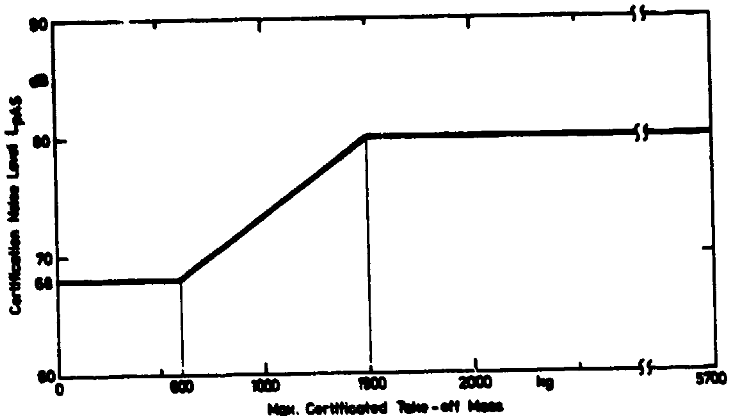

Fig. 2.15 ANNEX 16, Chapter 6 noise limits

The certificating authorities may, at their discretion, request the flyover-noise to be evaluated in terms of EPNL. However, EPNL-limits have not been defined yet and only "A-level-limits" are established and in use, as shown in Fig. 2.15. For convenience, the noise limits in $L_{pA,max}$ and the mass-break-points are presented in TABLE 3 below.

TABLE 3 Chapter 6 noise limits for light propeller-driven aeroplanes (level flyover procedure)

Flyover Noise Limit:	68 dB(A) up to 600 kg;	80 dB(A) from 1500 kg up to 5700 kg (9000 kg)

It should be emphasized that here the noise limit values vary linearly with mass between 600 kg and 1500 kg, rather than logarithmically, as was the case with heavy propeller-driven aeroplanes in the Chapter 3 procedure. A logarithmic variation of course is less stringent, than a linear one.

2.5.4 Reference and Permissible Test Atmospheric Conditions

Only two atmospheric parameters are specified to determine the reference flight procedure (engine power and flight speed related) and to correct the noise-level data:

- o sea level atmospheric pressure of 1013.25 hPa;
- o ambient air temperature 25 °C (i. e. ISA + 10 °C).

The following test-windows (under conditions of no precipitation) have been established

- wind speed (measured 1.2 m above ground, instead of 10 m as for heavy aeroplanes) must not exceed 19 km/h, but if in excess of 7 km/h, the flight direction shall be so aligned that it does not deviate by more than 15° from the wind-direction;
- ambient air temperature T must not be below 2 °C and not above 35 °C;
- relative humidity RH must not be below 20 % and not above 95 %.

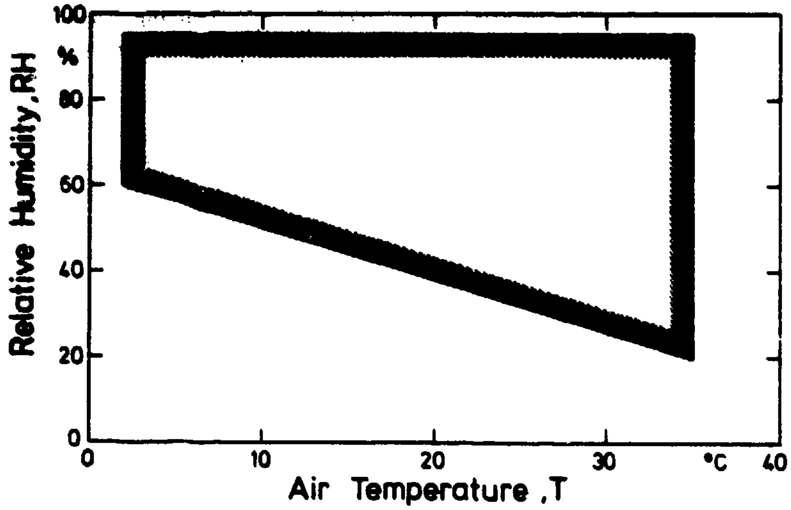

Fig. 2.16 Area of permitted combinations of relative humidity and air temperature for noise certification testing of ("light") propeller-driven aeroplanes not exceeding 5700 kg take-off mass after ANNEX 16, Chapter 6

Again, certain combinations of T and RH are to be avoided, as shown in Fig. 2.16. As for heavy aeroplanes, conditions causing excessive atmospheric attenuation at high frequencies are not allowed. Furthermore, no temperature inversion should exist, which might cause sound-reflections from above the aircraft towards the ground-based microphone. It is often difficult to determine the presence of a temperature- inversion, unless such information is available from a nearby weather-station. Of course, the test aeroplane itself, or a companion aeroplane could directly determine an altitude/temperature-profile, to ensure that acceptable test-conditions prevail. Usually, such an effort is not undertaken in the noise certification of light propeller- driven aeroplanes.

2.5.5 Determination of Aircraft Height

Only the height (rather than an entire flight path) and deviation from the vertical to the microphone are of interest in certification noise testing of light aeroplanes. They must be determined by an aircraft-independent means, such as a ground based tracking-system (theodolite, triangulation or radar). Aircraft velocity over ground does not enter into the noise evaluation, as an EPNL-value is not required. Therefore, there is no need for a very sophisticated tracking system; in fact, photographs taken by one high quality camera (preferably with a Polaroid-film-plate, to allow instant evaluation of flight validity) that points exactly vertically towards the aircraft in flyover suffices. This way it is possible to determine "on-line" (1) flight-height, (2) lateral displacement, and (3) yaw-angle, with an accuracy - as practice has shown - is sufficient for correction purposes. Apart from the prohibitive cost of operation and set-up, kinetheodolite or radar-tracking would not allow an on the spot decision whether a flight was valid with respect to a height/lateral-deviation. Polaroid-camera shots provide, however, such information after about one minute. If necessary, the pilot can then immediately be asked to repeat the test.

2.5.6 Acoustic Data Acquisition

The noise measuring station may consist of one microphone only, positioned directly under the flight path and approximately (!)* 1.2 m above ground, again in an area that should be flat and free. Fig. 2.17 illustrates these requirements. The grazing-incidence condition is recommended calling for a pressure-type microphone to avoid directional sensitivity-changes during flyover. Electronic and ambient background noise must be recorded with the same gain-settings as used in the actual noise measurement, and the maximum aircraft radiated noise should exceed the background noise by at least 10 dB. (It will be shown in Section 4.3.3 of this AGARDograph that such a signal-to-noise ratio does not suffice to correct for adverse ground-reflection effects induced by the microphone position 1.2 m above ground.

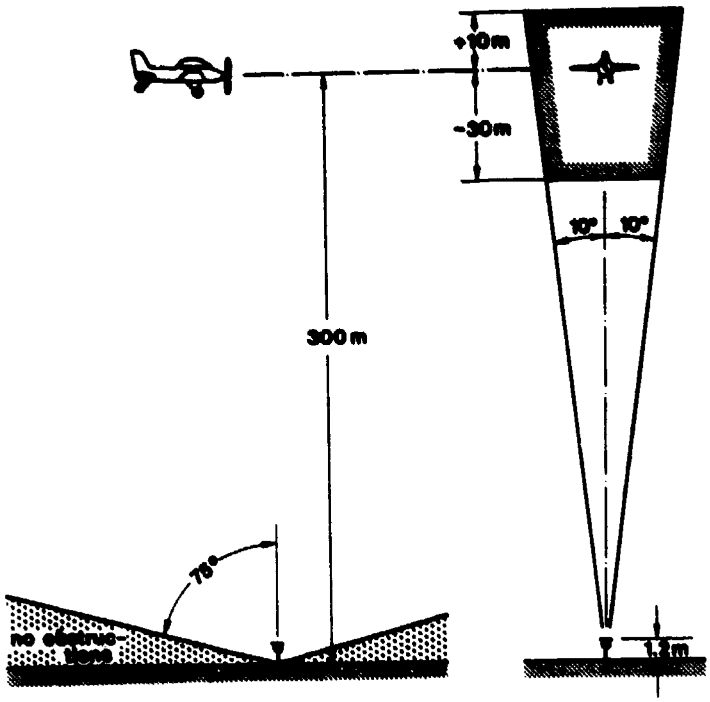

Fig. 2.17 Flight corridor test requirements for noise certification of "light" propeller driven aeroplanes not exceeding 5700 kg take-off mass

2.5.7 Data Adjustment

(a) Correction for Noise Received on the Ground

If outside the test-height window, ANNEX 16 requires a distance correction based solely on the inverse-square law for flight heights differing from 300 m. Atmospheric attenuation need not be considered, since the spectral maximum of the noise of a typical light propeller aeroplane lies below 1000 Hz, where atmospheric attenuation is negligible for the relatively small propagation distances involved.

(b) Source Noise Correction

The effect of ambient temperature on the (helical) blade tip Mach-number (HTM) is specifically singled out for source-correction. Only very small deviations from the reference Mach number are permitted without correction; allowable deviations have been specified as

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* This exclamation mark should emphasize the fact that the term "approximately" - as specified in ANNEX 16/Chapter 6 - is rather badly chosen. Even minor position-changes of the order of centimeters will have a pronounced effect on the measured signal.

- 0.014 for helical blade tip Mach numbers at and below 0.700,
- 0.007 for helical blade tip Mach numbers above 0.700 up to and including 0.800,
- 0.005 for helical blade tip Mach numbers above 0.800.

When the deviations are larger, a correction $K \log (M_R/M_T)$ must be added to the noise levels, where M_R and M_T are the reference and the test helical blade tip Mach numbers, respectively.

The value of K must be obtained from approved data of the test aeroplane or from dedicated flight tests where air speed and propeller rotational speed are varied appropriately. This latter approach is, however, much disputed, since engine noise contributions, which have a different rotational-speed dependence than propeller noise, are not correctly accounted for. Efforts by CAEP to develop a more straightforward temperature and/or helical tip Mach number correction are discussed in Section 4.6.2 of this AGARDograph. Also, it must be cautioned again that such ad hoc flight tests must be done with a ground board microphone, as grave errors may result when the customary "1.2-m-microphone" is used.

In the absence of flight test data a value K = 150 should be used if M_T is less than M_R. Otherwise, no correction is applied.

(c) Validity of Test Results

As for the heavy aircraft the validity of data is established if the confidence-limit does not exceed +/- 1.5 dB at a 90% confidence level. For the light propeller-driven aeroplanes, however, a minimum of 4 (rather than 6) "valid" test-flights suffices. (See also AGARDograph Appendix E).

(d) Performance Correction

Since only straight level flights are specified in the certification procedure (but no take-offs, into which the performance of an aircraft would enter directly), light propeller-driven aeroplane noise certification according to the Chapter-6 procedure requires a performance correction "from the books".

The ANNEX states that the performance correction is intended to reward higher performance aeroplanes for their ability to climb steeper angles and thus gain altitude faster, implying that the greater effective distance results in less noise.

In essence, the performance correction takes into account how much more ("Bonus") or less ("Malus") altitude than 300 m above a reference point at 3500 m after brake-release the aeroplane would have attained based on the achievable take-off distance and climb performance. The procedure is shown in Figs 2.18a and b. The take-off distance counts from the brake-release point to the point where the aeroplane has cleared a 15 m high obstacle. The slope (angle with the ground plane) of the climb is defined by the best rate-of-climb, R/C, and the speed V_y for that particular best rate-of-climb. Since the reference altitude of 300 m is in the denominator, a "Malus" comes out as a positive value, to be added to the certification level.

A typical case illustrates the correction procedure. Assume that a particular aeroplane has the following performance data, as specified in the operators handbook.

For example:

- Best rate of climb at 0 m: 3.25 m/s
- Speed for best rate of climb: 38.9 m/s
- Take-off distance at take-off power to clear 15 m high obstacle: 548.6 m

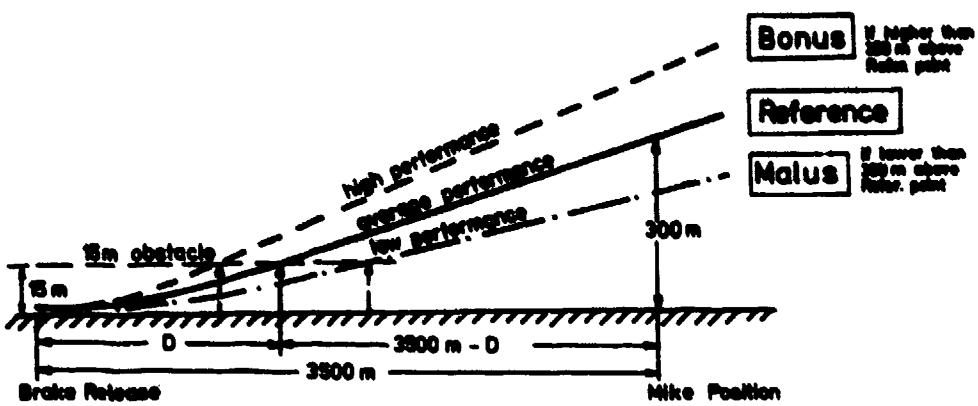


Fig. 2.18a "Performance correction"-philosophy for "light" propeller driven aeroplanes not exceeding 5700 kg take-off mass

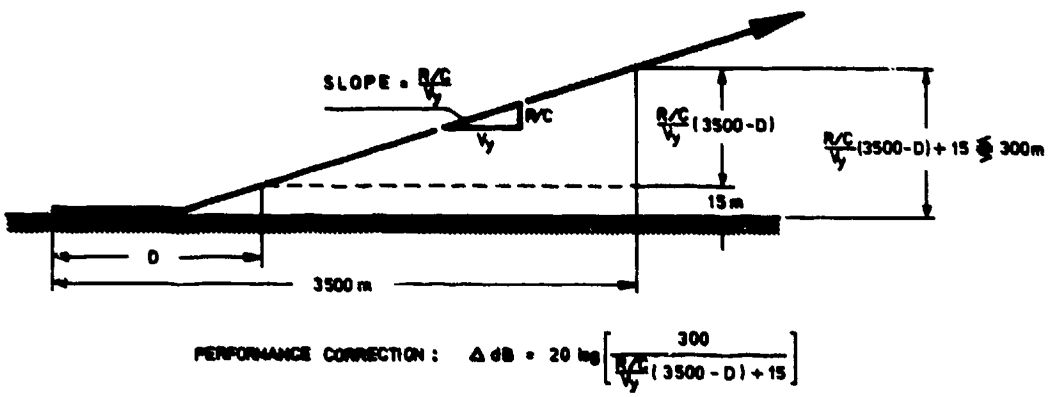


Fig. 2.18b Flight path related geometry for "performance correction"

The height above the reference point would then be 262 m (instead of 300 m), hence a "Malus" of 1.2 dB must be added to the (corrected) certification level.

The performance correction is done entirely on paper with the performance data provided by the manufacturer for standard day conditions (15 °C, not the 25 °C of other requirements). It can be considered as a way of converting a level flight noise measurement into a simulated take-off fly-over measurement by a simple test (i.e. the 300-m straight and level flight) and the above correction method.

The presently used "Performance Correction" is however rather disputed. For this reason, among others, the revised noise certification for light propeller-driven aeroplanes has been established and included in the ANNEX 16 as a new Chapter 10. This new noise certification procedure will be described in the following Section.

2.6 Noise Certification of Light Propeller-driven Aeroplanes: New Procedure (ANNEX 16: Chapter 10 and Appendix 6)

Experience over the past several years in the application of the Chapter-6/Appendix-3 noise-certification procedure for propeller-driven aeroplanes not exceeding 5700 kg had raised serious doubts on the validity of the ensuing certification noise level as a true measure of people's annoyance. Communities close to airports seem more irritated by the frequent take-offs and initial climbs of the (light) propeller aircraft, than by flyovers at medium or high altitudes. It seemed logical, therefore, to propose a noise certification scheme that includes an actual take-off test procedure. The task at hand was to develop new noise certification procedures without adding undue complexity to those presently in use.

A take-off test for the light aircraft would provide at least two distinct advantages: The test would better reflect what many regard as the most annoying part of the flight (the initial climb) and it would inherently account for the aircraft's performance, as a "poor climber" would pass over the microphone at a lower height and thus cause higher noise levels, and vice versa.

Questions to be addressed were the engine power to be employed (whether a one or a two-segment take-off should to be selected), the noise measure (whether again the maximum A-weighted level was to be used, or perhaps a time duration corrected A-level, such as the "Sound Exposure Level, L_{pAE}", or even a time duration and tone corrected level, such as the "Effective Perceived Noise Level, EPNL"). Furthermore the minimum number of required test flights was to be determined (four or six, for example), as well as the atmospheric and flight operational reference and measurements conditions and the appropriate correction procedures from test to reference.

Many field evaluation tests have been conducted in the process of developing the new scheme. As a result of these efforts, the following new noise certification procedure for light propeller-driven aeroplanes has been developed by CAEP and has been made a Standard in the ANNEX 16 as a new Chapter 10.

2.6.1 Applicability

The Standard applies to all propeller-driven aeroplanes and their derived versions (other than aerobatic, fire-fighting and agricultural) with a maximum certificated take-off mass not exceeding 9000 kg, for which the prototype airworthiness application was accepted on or after 17 November 1988.

2.6.2 Reference Noise Measurement Point and Flight Procedure

The test aircraft - at maximum take-off mass - must conduct a minimum of 6 take-offs with take-off power until it has cleared a point 15 m above the runway (first phase). It may then retract the undercarriage and adjust the flap-settings to its normal climb configuration and continue its flight with maximum continuous engine power (unless airworthiness-related limitations apply) to achieve its then best rate-of-climb speed V_y +/- 9 km/h (second phase). This procedure defines the **reference flight path.**

The climb configuration and speed must be maintained until well beyond the **reference noise measurement point** which is located 2500 m from the brake-release point on the runway centerline. This point must be overflown within a lateral deviation of no more than +/-10° from the vertical and within +/-20% of the reference height (Fig. 2.19). This seemingly large margin in the allowed deviation from reference height reflects the fact that height deviations can be easily corrected on the basis of the inverse square distance law for an $L_{pA,max}$-value.

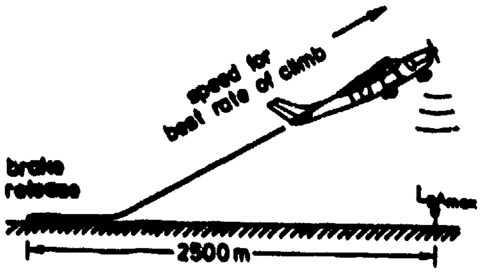


Fig. 2.19 ANNEX 16, Chapter 10 noise certification procedure

2.6.3 Noise Evaluation Measure and Noise Limits

Although originally the time-duration corrected noise measure L_{pAE} was preferred, field tests have shown that there exists an approximately linear relationship between the noise measures L_{pAE} and $L_{pA,slow,max}$. The suffix "slow" in the noise measure relates to the measuring instrument detector time constant of 1000 ms. Since noise limits had to be newly established, anyway, it was decided to revert to the simpler to determine $L_{pA,slow,max}$ as the pertinent noise evaluation measure.

The proposed take-off mass dependent noise limits are shown in Fig. 2.20 and listed again in TABLE 4, for convenience. Note that the mass-scale is logarithmic!

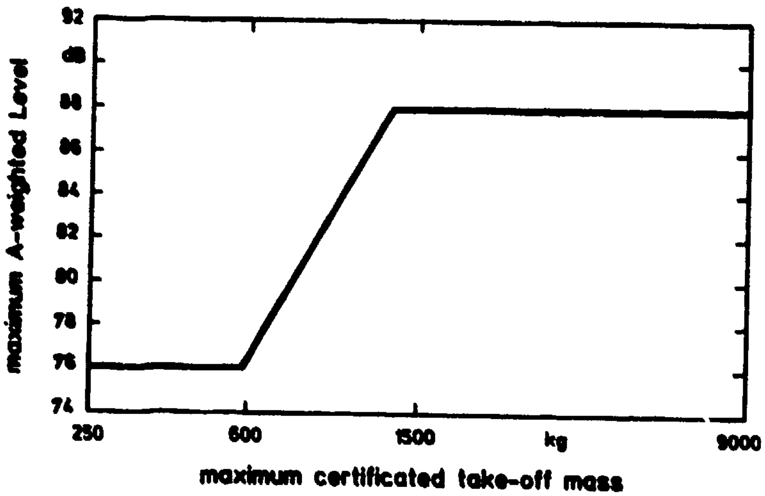


Fig. 2.20 ANNEX 16 Chapter 10 noise limits

TABLE 4 Chapter 10 Noise Limits for light propeller-driven aeroplanes (take-off procedure)

Flyover Noise Limit:	76 dB(A) up to 600 kg;	88 dB(A) from 1400 kg up to 9000 kg

It should be emphasized that these (seemingly high) levels correspond to pressure-doubled levels, as measured directly on an acoustically hard surface, rather than 1.2 m above ground (see Section 2.6.6)

2.6.4 Reference and Permissible Test Atmospheric Conditions

The atmospheric conditions must be measured 1.2 m above ground, rather than at 10 m, as for the heavy aeroplanes. The reference conditions (towards which acoustic data are to be corrected) are specified as follows:

- Sea level atmospheric pressure 1013.25 hPa
- Air Temperature 15 °C (i.e. ISA)
- Relative Humidity 70%
- Zero Wind

The differences with the Chapter 6 conditions are the reference temperature, now set at 15 °C, and the specification of a reference relative humidity. There are also some minor differences in the allowable test-windows, which are specified as

- No precipitation
- Reported wind not above 19 km/h and cross wind not above 9 km/h (30 second average), measured 1.2 m above ground
- Relative humidity along the entire noise propagation path not higher than 95% and not lower than 20%
- Ambient temperatures not above 35 °C and not below 2 °C

Fig. 2.21 shows the temperature/relative-humidity area. Within this area an RH/T-regime is defined where no atmospheric absorption corrections are required.

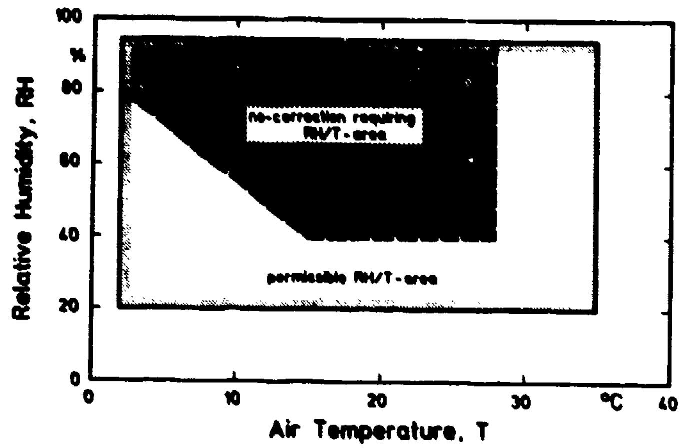


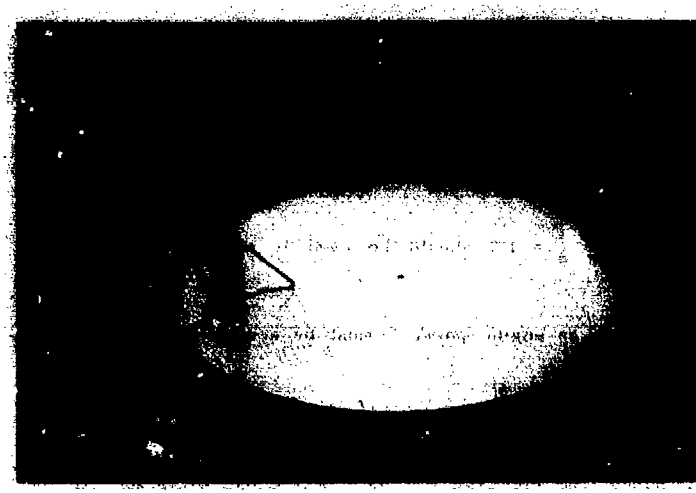
Fig. 2.21 Area of permitted combinations of relative humidity and air temperature for noise certification testing of "light" propeller-driven aeroplanes not exceeding 9000 kg take-off mass after ANNEX 16, Chapter 10

2.6.5 Flight Path Tracking

The flight path must be monitored in an appropriate manner to allow later data correction for differences between test and reference flight height. Since only a maximum A-weighted level is required for certification, tracking can be done again by means of (polaroid) cameras, positioned at appropriate distances ahead, under and aft of the reference noise measurement point, for "straight-up"-shots. A minimum of two cameras is necessary (and often sufficient) to interpolate to the position exactly above the reference noise measurement point.

2.6.6 Acoustic Data Acquisition

For the first time in the practice of noise certification a change from the customary microphone position 1.2 m above the ground has been specified in the Chapter-10 procedure. In measuring propeller noise with elevated microphones, significant signal distortions are observed; these result from the superposition of the direct sound wave and the ground-reflected wave at the microphone. The two waves can "erratically" attenuate or amplify the original acoustic signal. Corresponding problems are avoided by the use of a microphone very close to (or even flush with) the ground where ground-reflections inherently cannot occur. Accordingly, it is specified that the microphone must be positioned off-center and in an inverted manner with its protective grid 7 mm above a white painted metal circular plate of 40 cm in diameter. There is nothing magic with the value of 7 mm for the microphone distance above the plate. Here, slight deviations of, say, +/- 1 or 2 mm can be tolerated, as the main effect of this arrangement is to shift the first cancellation dip to



frequencies well above the range of interest. This is achieved for such small distances of the order of 7 mm.

A photograph of such an arrangement is shown in Fig. 2.22. The noise limits specified in 2.6.3 above refer to such a microphone arrangement.

Fig. 2.22 Inverted microphone arrangement

2.6.7 Data Adjustment

(a) Correction for Noise Received on the Ground (Delta M and Delta 1 terms)

When outside the atmospheric-absorption area where no correction is required (see Fig. 2.21), differences from reference atmospheric absorption can be accounted for by adding to the measured noise level a term

$$\text{Delta M} = 0.01\ (H_T \cdot \alpha - 0.2\ H_R)$$

where H_T is the actual height and H_R is the reference height (in meters) of the test aircraft above the reference noise measurement point, and α is the rate of absorption at 500 Hz, as listed in the appropriate Tables (see Ref. 3 and Appendix D of this AGARDograph).

To account for differences in the height, a term

$$\text{Delta 1} = 20 \log (H_T/H_R)$$

is added to the measured noise level, if test conditions are outside the no-correction area as shown in Fig. 2.21. Otherwise, the correction term should be

$$\text{Delta 1} = 22 \log (H_T/H_R).$$

The change in the value of the factor from 20 to 22 is introduced to somehow compensate for an additional absorption effect outside the "no-correction-window".

(b) Source Noise Correction (Delta 2 and Delta 3 terms)

Following the same argumentation as put forward in the temperature and helical tip Mach number correction, respectively, for the light propeller aircraft certification according to ANNEX 16/ Chapter 6, only small deviations from the reference Mach number are permitted without correction. The same allowable deviations have been specified as

- 0.014 for helical blade tip Mach numbers at and below 0.700,
- 0.007 for helical blade tip Mach numbers above 0.700 up to and including 0.800,
- 0.005 for helical blade tip Mach numbers above 0.800

When the deviations are larger a correction must be added to the noise levels equal to

$$\text{Delta } 2 = K_2 \log (M_T/M_R)$$

The value of K_2 must be obtained from approved data of the test aeroplane, or from dedicated flight tests as described in Section [illegible] above.

In the absence of flight test data, a value $K_2 = 150$ should be used if M_T is less than M_R. Otherwise, no correction is applied.

The effect of ambient pressure or temperature on engine power P must be accounted for by adding another term to the measured noise level:

$$\text{Delta } 3 = K_3 \log (P_R/P_T)$$

Again, the value of K_3 shall be determined from approved test data of the test aeroplane. In the absence of such date, a value $K_3 = 17$ can be used.

(c) Validity of Test Results

The final noise certification level is the average of at least 6 "valid" flyover noise levels, appropriately corrected as per section (a) and (b) above. The statistical 90% confidence limit, based on these six (or if necessary, more) samples must again not exceed +/- 1.5 dB. (See also AGARDograph Appendix E).

2.6.8 Fall-back Provision

For a few years after the introduction of this new 'Chapter 10/Appendix 6 Standard' a fall-back provision is foreseen in order to avoid undue hardship on aircraft manufacturers and operators. Aeroplanes which fail to comply with the Standards of Chapter 10 would be allowed to go through a noise certification test according to Chapter 6/Appendix 3.

2.7 Noise Certification of Helicopters (ANNEX 16: Chapter 8 and Appendix 4)

Serious efforts to develop 'Standards and Recommended Practices' for the noise certification of helicopters began at the fifth meeting of the ICAO Committee of Aircraft Noise in 1976 (CAN/5). Initially, in an attempt to encompass the entire range of operational manoeuvres of a helicopter, a very elaborate test-scheme was proposed, where four flight conditions were to be evaluated. First, the helicopter was to hover at a distance of 200 m from an array of microphones at several heights above the ground at 8 different nose directions. Second, landing-approaches were to be conducted at flight path angles of 3°, 6°, and 9°. Third, horizontal flyovers at 2 heights and at 3 flight-speeds, and fourth, simulated take-offs at the best rate-of-climb speed were to be executed. All flyovers had to occur above a laterally extended acoustic measurement array.

Preliminary testing along these lines showed that such a procedure was unnecessarily complex. It was found, for example, that in hovering the helicopter had to be constantly stabilized. This caused large dispersions in the noise-emission. Also, since the distance in the approach and the take-off flight procedure between the vehicle and the microphone was comparatively small, slight deviations from a reference flight-path caused large variations in the noise-level.

In the time-span between CAN/5 (1976) and CAN/6 (1979) a consolidated proposal for a helicopter noise certification procedure for inclusion into the ANNEX 16 as Chapter 8 and Appendix 4 was worked out and has been made a Standard in 1981. The new Standard contains fewer and less comprehensive flight procedures and conditions; notably, the hover-test was eliminated. Further amendments were made at CAN/7 (1983).

2.7.1 Applicability

The Standard is applicable to helicopters (other than special purpose types) for which the airworthiness application was accepted on or after 1 January 1985. The cut-off date for derivatives (changes in type design) has been set as 'on or after 17 November 1988'.

2.7.2 Reference Noise Measurement Points and Flight Procedures

The helicopter to be tested must conduct a series of take-offs, level flyovers, and landing-approaches. In each case, the craft must fly over the noise measuring station which consists of a centrally located microphone at the flight path reference point (C ≙ center microphone) and two additional microphones, symmetrically placed 150 m to the left and to the right of the flight track, as shown in Fig. 2.23 (L ≙ left-hand microphone, R ≙ right-hand microphone with respect to the flight direction).

(a) Take-off

The **reference take-off flight path** (Fig. 2.23a) is defined by a straight horizontal line at a (flight) height of 20 m above ground (connection of points A and N) and a subsequent ascending, straight line given by the helicopters best rate-of-climb (connection of N and F). To follow this reference take-off flight path (with a kink at point N at the intersection of AN and NF) the pilot must initiate climb at point B, i.e. some distance before reaching N in order to intercept the reference climb path. Thus the location of point B can vary and must be determined through pretest flights.

Point K, the **take-off reference noise measurement point**, is the location of the center noise measurement station at 500 m past N. Point F on the reference profile is directly above point M. Noise measurements start when the helicopter flies over point T and ends when the helicopter flies over point M. The time span TM must be determined such that it begins well before, and ends well beyond, respectively, the "10-dB-down-time" of the noise of the helicopter in flyover.

To execute the take-off test procedure, the helicopter must be stabilized in level flight at a height of 20 m and at the best-rate-of-climb speed V_y at point A (see Fig. 2.23a); it continues in level flight to a point B, where the maximum take-off power (corresponding to the minimum installed engine specification power* or gear-box torque, whichever is lower) is applied and a steady climb initiated. Steady climb conditions are reached at point N. These must be maintained at least throughout (better still well beyond) the "10-dB-down-time". During climb, the rotor speed is stabilised at the maximum normal operating RPM certificated for take-off (≙ 100% RPM). Also, the helicopter must be in its maximum certificated take-off mass.

(b) Level Flyover

For level flyover (Fig. 2.23b) the helicopter must be in the cruise configuration and must be stabilised in level flight overhead the **flyover reference noise measurement point** at a height of 150 m.

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* The term "minimum installed engine specification power" defines the minimum average fleet specification engine power

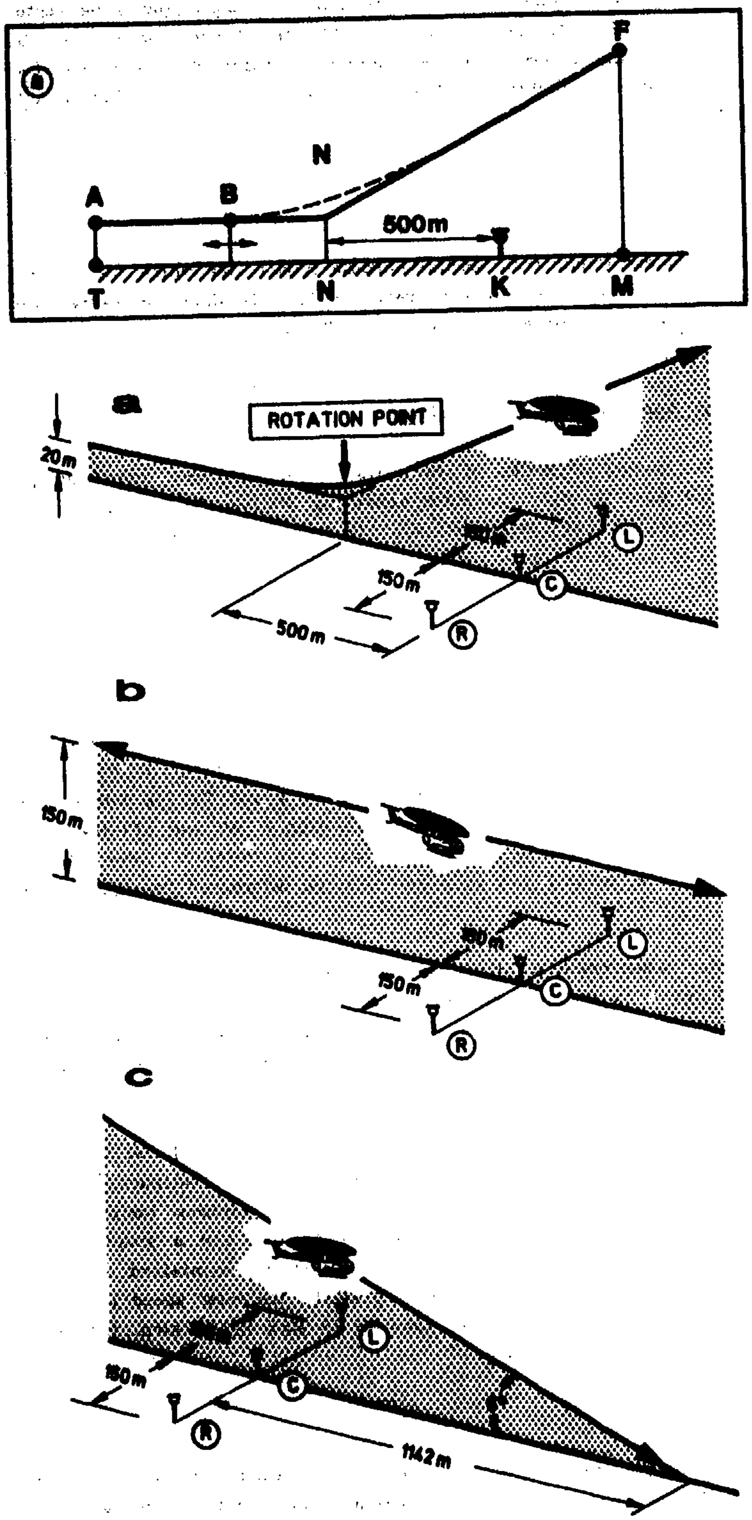


Fig. 2.23 Noise certification test procedure for helicopters:
top - takeoff
center - level flyover
bottom - landing approach

The flight speed must be the lesser of 0.9 V_H (or 0.9 V_{NE}) or 0.45 V_H + 120 km/h (or V_{NE} + 120 km/h), where V_{NE} is the "never exceed speed", and V_H is defined as the airspeed in level flight using the torque at minimum installed, maximum continuous power under 1013.25 hPa ambient pressure and 25 °C ambient temperature. The rotor-speed must correspond to the maximum certificated normal operating RPM (≙ 100% RPM) for level flight. Again the helicopter mass must correspond to the maximum certificated take-off mass.

(c) Approach

For landing approach (Fig. 2.23c) the helicopter shall be stabilized in its landing configuration (e.g. landing gear down if applicable) and must follow a 6°-approach path, such that it overflies the approach reference noise measurement point at a height of 120 m. Flight speed must be the best-rate-of-climb speed V_y and rotor speed the maximum certificated normal operating RPM for approach flight (≙ 100% RPM). The helicopter mass must correspond to the maximum certificated landing mass.

3.7.3 Noise Evaluation Measure and Noise Limits

Initially, the "maximum A-weighted flyover noise level, L_{pAmax}", was considered an appropriate noise evaluation measure, since the helicopter frequently operates in areas, where community noise is also measured in dB(A). However, since other aircraft, such as the heavy propeller-driven aeroplane and subsonic jet-aircraft are noise-certificated in terms of EPNL, homogeneity with these was considered more important to allow a direct comparison, and the EPNL was selected as the noise evaluation measure.

To derive appropriate noise limits, all available data at the time (prior to CAN/7) on current helicopters were utilised. In drawing the noise-limit line, allowances had been made for foreseeable technical advances and measurement uncertainties. Fig. 2.24 shows the noise limits in terms of mass-dependent EPNL-values for the three flight-procedures take-off, flyover, and approach, as agreed at CAN/6 (1981) and as revised and presently in force since CAN/7 (1983).

For convenience, the mass-dependent noise limits in EPNdB for the three test procedures and the respective break-points are listed in TABLE 5 below (note that a logarithmic mass-scale is used, as with the subsonic jet and heavy propeller-driven aeroplanes):

TABLE 5 Chapter 8 Noise Limits for Helicopters after CAN/7

Take-off Noise Limit:	89 EPNdB up to 788 kg;	109 EPNdB above 80,000 kg
Overflight Noise Limit:	88 EPNdB up to 788 kg;	108 EPNdB above 80,000 kg
Approach Noise Limit:	90 EPNdB up to 788 kg;	110 EPNdB above 80,000 kg

2.7.4 Reference and Permissible Test Operational and Atmospheric Conditions

The following reference conditions for helicopter noise certification testing have been established

- o sea-level atmospheric pressure of 1013.25 hPa;
- o ambient air temperature of 25 °C (i.e. ISA + 10°C);
- o relative humidity of 70 %;
- o zero wind.

Certification noise measurements may however be conducted within the same atmospheric windows as applicable to subsonic jet aeroplanes or heavy propeller-driven aeroplane testing, i.e. under the following conditions:

- o no precipitation
- o ambient air temperature (T) measured 10 m above ground must not be below 2 °C or above 35 °C;
- o relative humidity (RH) along the entire noise propagation path must not be below 20 % or above 95 %;
- o certain combinations of RH and T that would result in an atmospheric sound attenuation in excess of 12 dB/100 m in the 8-kHz-1/3-octave-band must be avoided (see Fig. 2.9);
- o the average wind must not exceed 19 km/h and the cross-wind component (relative to the flight direction) must not exceed 9 km/h. If a head or tailwind affects the overground speed, this fact must be accounted for in the EPNL-computation process. Specifically, if in the level flight test procedure, the difference between airspeed and ground speed exceeds 7 km/h, then flights should be made in equal numbers with and against the wind direction.

Also for measurements, the following maximum deviations from reference conditions are permitted

- o deviation from the vertical above the reference track +/-10°
- o flight speed deviation from reference +/- 9 km/h
- o mass deviation from reference -10%/+5%
- o rotor rotational speed within +/-1% of 100% RPM

Originally, there had been a "no-correction window". Regimes of certain atmospheric and operational parameters had been defined where - if prevailing - no subsequent data correction would have been necessary. However, helicopter noise was found to be very sensitive to even minor deviations especially from operational reference parameters such that at present there is no no-correction window, and all data must be corrected towards reference conditions. As there is still not sufficient information available on the effect of various operational and flight parameters on the final EPNL-value, future adjustments to the permissible test window (in terms of a narrowing or widening) cannot be excluded.

2.7.5 Flight Path Tracking

As with all aircraft that are noise-evaluated on the basis of an EPNL-value, precise flight path tracking is necessary. This must be done by an aircraft-independent means, preferably involving kinetheodolites, radar- or laser-equipment. Frequently, a method is recommended where at least 3 vertically mounted cameras on the intended track, approximately 500 m apart are used in conjunction with radio altimeter data from on - board systems. The photographs thus taken are used to establish the helicopter's height and its lateral off-set.

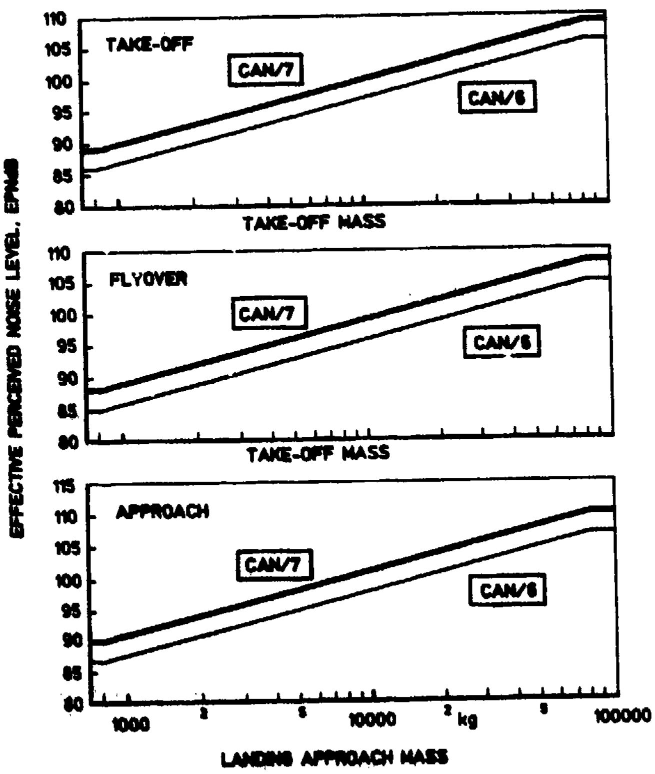


Fig. 2.24 ANNEX 16 Chapter 8 noise limits per CAN/6 and CAN/7 for test procedures 'take-off', 'level flyover' and 'landing approach'

2.7.6 Acoustic Data Acquisition

Acoustic data must be acquired by pressure-type microphones positioned 1.2 m above ground. No changes - say towards employing ground-proximity microphones - are presently envisioned, since the helicopter noise spectra are thought to be less vulnerable to ground-reflection effects than those of a light propeller aircraft. Similar considerations as advanced in Section 2.4.6 for the heavy propeller-driven aeroplanes also apply to the other aspects of the acoustic measurement procedures for helicopters.

2.7.7 Noise Data Adjustment

As stated already, all data <u>must</u> be adjusted towards reference conditions, involving again a source-to-ground path correction (Delta 1 and Delta 2) and a source correction (Delta 3).

(a) Source-to-ground-path Correction (Delta 1 and Delta 2 terms)

The difference in atmospheric attenuation as a result of differences between reference and test flight path, as well as in atmospheric conditions must be accounted for in the evaluation of the measured data. The procedure corresponds to the one discussed in Section 2.4.7, relating to a Delta 1 adjustment of the measured EPNL-value. However the total allowed adjustment for the Delta 1 term shall not exceed 4 EPNdB.

Deviations in the test flight speed and height from reference enter the calculation of the EPNL by virtue of a change in effective ground speed and the ensuing change in sound exposure duration which requires a Delta 2 adjustment of the measured EPNL-value, again corresponding to the one discussed in Section 2.4.7. However, the total allowed adjustment for the Delta 2 term shall not exceed 2 EPNdB.

(b) Source Correction (Delta 3 term)

For a level flight condition helicopter source noise is distinctly determined by the main rotor advancing blade tip Mach-number and thus very sensitive to even slight changes in RPM and flight speed. Corrections must be made on the basis of a "noise sensitivity evaluation". A noise sensitivity curve relates the Perceived Noise Level (PNL) to the advancing blade tip Mach number, computed from true air speed, outside temperature and rotor speed. By varying one or several of these primordial parameters and measuring the ensuing PNL-values during flyover one can derive a noise sensitivity curve which can then be used for the source noise adjustment towards reference conditions in terms of the required Delta 3 term. An example of such a procedure is discussed in Section 3.6.2, an appropriate illustration appears later in this AGARDograph as Fig. 3.58.

(c) Test Result Validity

Each test-flight produces one EPN-level at each of the three microphones. ANNEX 16 requires that these 3 EPNL-values are arithmetically averaged to arrive at <u>one</u> certification EPN-level. Also, a minimum of 6 <u>valid</u> test flights (for each procedure) is to be conducted and the ensuing EPNL-values must be further averaged to determine (in a statistical sense) the mean and the standard deviation of the mean, to establish a 90% confidence-limit not to exceed +/- 1.5 EPNdB. (See also AGARDograph Appendix E).

(d) Trade-offs

Trade-offs are allowed, if noise limits at one or two measuring points are exceeded. However, the sum of the excesses shall not be greater than 4 EPNdB, any individual excess at a measurement point shall not be greater than 3 EPNdB, and any excess shall be offset by a corresponding reduction at the other point(s). It will be noted that these trade-off allowances are more lenient than those applicable to heavy propeller aeroplanes and subsonic jet aircraft.

3. CERTIFICATION FLIGHT NOISE TESTING AND ANALYSIS TECHNIQUES

In the previous Chapter the noise certification test procedures as specified in the ICAO ANNEX 16 document have been presented in detail. In this Chapter the practical execution of noise certification testing and analysis will be discussed. Accordingly, there will be discussions on the acoustic and non-acoustic equipment needed either in the field for data acquisition or in the laboratory for data analysis; there will be discussions pertaining to the test preparation, to the test site selection, to equipment set-up and test conductance. The Chapter will conclude with a discussion of data analysis, specifically for determining the noise measures 'maximum A-weighted flyover noise level' and 'Effective Perceived Noise Level'. Excellent guidance material towards conducting flight noise measurements has been compiled in |4|.

3.1 Introduction

The basic equipment needed in the field for noise certification testing is shown in a block-diagram in Fig. 3.1. The noise measuring system as such (Fig. 3.2) consists of a data-acquisition block, a data-processing block and appropriate calibration instrumentation. Here, the data acquisition block includes microphones with preamplifiers, signal-conditioners, and analog or digital tape-recorders. The data processing block (if used in the field) could contain on-line spectrum analysers or would, as a minimum, consist of a sound-level meter to read overall unweighted or A-weighted noise levels. Noise-monitoring equipment should also be available, such as oscilloscopes or other suitable read-out instrumentation (graphic level recorders and/or printers). Calibration in the field would most likely be restricted to selected frequency-sensitivity checks using pistonphones. An overall frequency response calibration (over the entire frequency range of interest) would normally be done in the laboratory using electrostatic actuators in combination with discrete or broad-band signal generators prior and/or after the actual test.

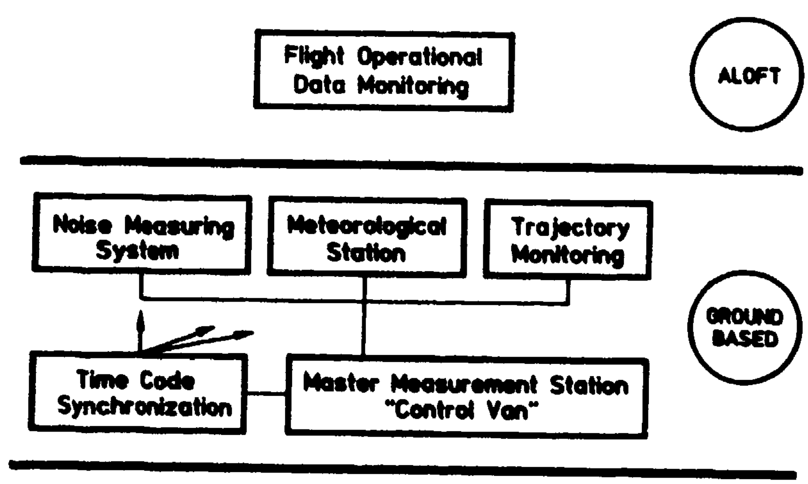


Fig. 3.1 Basic measurement-equipment needed in the field for noise certification testing

In addition to the noise measuring system, one or more ground based station(s) for meteorological data acquisition (wind, temperature, ambient air-pressure and humidity) are necessary. If such meteorological information was needed over the complete sound propagation path between the acoustic measurement station and the aircraft, weather balloons, sounding equipment (sodar), the test aircraft itself or an additional monitoring aircraft is used.

For aircraft trajectory monitoring one or several tracking station(s) are required using optical ground-based or on-board tracking systems or radio/radar tracking systems. The test aircraft itself is usually equipped with its own on-board data acquisition systems to monitor operational conditions, such as propeller or rotor rotational speeds, engine power, thrust, torque, manifold pressure, etc., as well as indicated air-speed, aircraft altitude and wind vector, outside temperature, humidity and pressure.

Communication between individual measurement stations, a nearby airport tower and the flight test crew is of the utmost importance both in terms of oral communication and time synchronization of acoustic and operational data. The central-, or master-, measurement-station will therefore contain appropriate radio- communication equipment, while all test personnel will carry individual "walkie-talkies".

More sophisticated recording and analysing equipment will be available in the laboratory, notably computer processing to handle the sometimes vast amounts of data.

In the following, Section 3.2 will treat acoustic test equipment, Section 3.3 other (non-acoustic) test equipment, i.e. tracking-, meteorological, time-synchronization and on-board instrumentation, Section 3.4 criteria for site-selection and test setup, and Section 3.5 details on the execution of the test. The final Section 3.6 will discuss the analysis and correction of acoustic data.

3.2 Acoustic Test Equipment

The entire acoustic data acquisition/reduction chain, as shown in Fig. 3.2, will now be discussed in detail. Photographs of some typical individual components of acoustic equipment appear at appropriate places in the text.

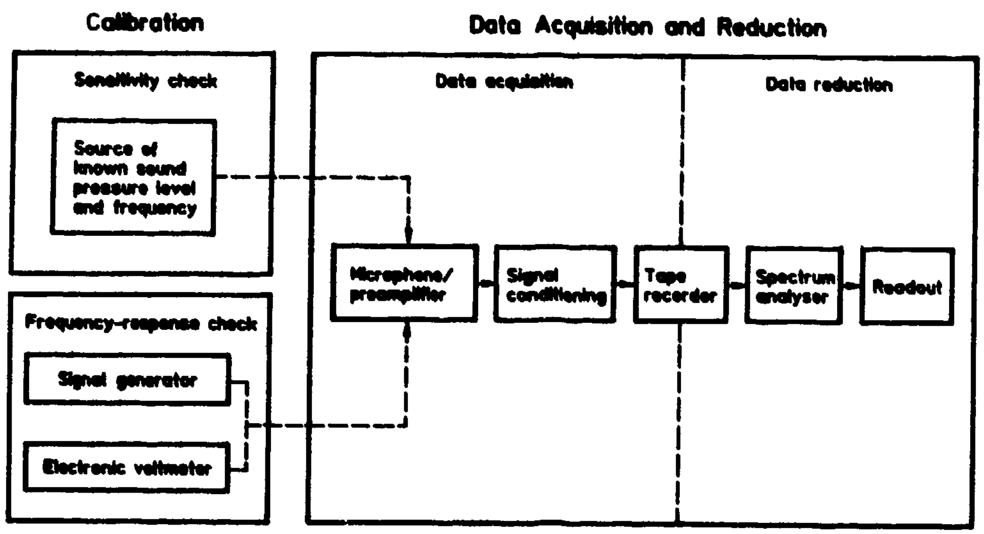


Fig. 3.2 Block diagram of noise measuring system for acoustic calibration, data acquisition and reduction (reproduced from |1|)

3.2.1 Data Acquisition

(a) Condenser Microphones: Types and Characteristics

For aircraft noise testing, condenser-microphones are recommended since they offer long term stability, operational reliability and robustness. There are basically three types of condenser microphones: free-field-, pressure- and diffuse-field-microphones. Of these pressure-type and free-field microphones can be used in measuring aircraft noise, whereas diffuse-field microphones are not suitable. An extensive discussion on microphone characteristics appears in |5|.

Since microphones are probably the most important link within any acoustic measurement chain, their characteristics should be well understood. Thus, for example, one must clearly distinguish between the (frequency-dependent) pressure sensitivity of a microphone and the (likewise frequency-dependent) pressure-increase on the microphone diaphragm due to the physical dimensions of the microphone.

The pressure response of a microphone is best determined by applying a defined pressure frequency sweep in a small cavity placed atop the microphone diaphragm. Clearly no directivity aspects enter, as there is simply a pressure atop the diaphragm within the cavity. If the pressure response of a microphone must be determined "under less favorable conditions", i.e. in a freefield environment by applying a plane wave frequency sweep, there will be an effect of the microphone body. This body causes an effective change (increase or decrease) of the pressure on the microphone diaphragm. The value of this pressure change is frequency-dependent but depends also on the angle of sound incidence. This is illustrated in Fig. 3.3 for several B&K 1/2-inch condenser microphones as indicated.

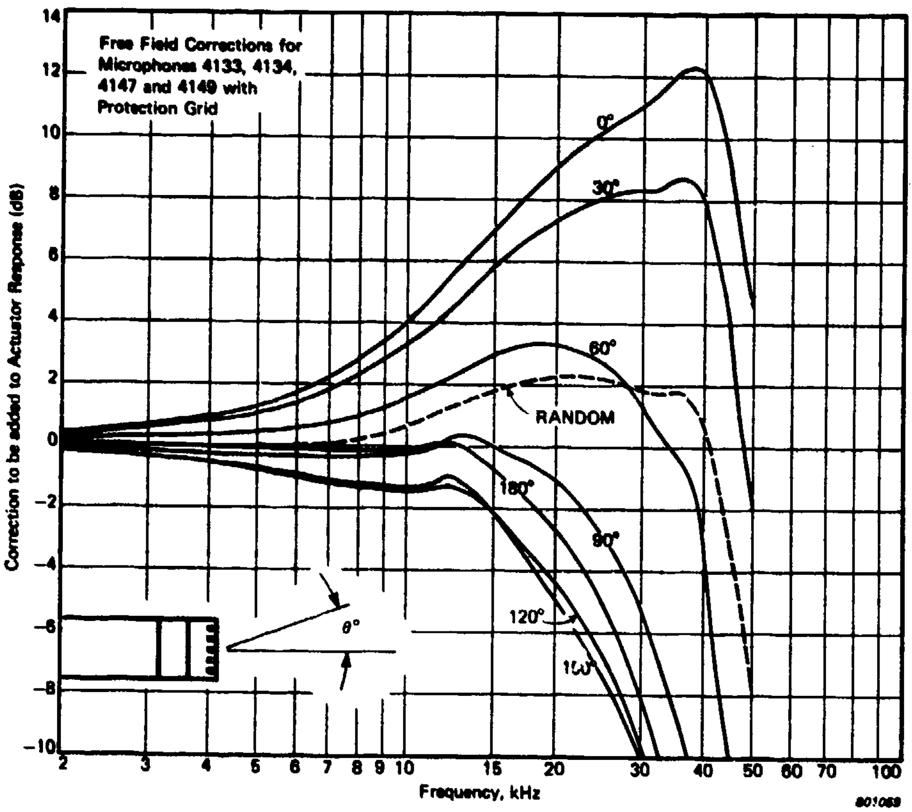


Fig. 3.3 Pressure increase on microphone diaphragm as function of frequency for different sound incidence angles

To obtain the freefield sound pressure (value of the sound pressure as if the microphone was not there) as resulting from a sound source in a known direction one has to add the 'Delta p' values from the measured sound pressure. For example, if the sound wave impinges under a 0 degree angle of incidence 4 dB at 10 kHz and 9 dB at 20 kHz must be subtracted. If the microphone is turned by

90°, such that the sound from that source now impinges at "grazing incidence" i.e. under a 90 degree angle of incidence, one would have to subtract 0 dB at 10 kHz and add 1 dB at 20 kHz. If the sound comes from the rear i.e. with an incidence angle of 180 degrees then one must subtract 0 dB at 10 kHz and add 3 dB at 20 kHz.

One might now appreciate why ICAO recommends the use of such a "pressure response" microphone to be adjusted for a grazing incidence angle with respect to the incoming sound wave: for such a 90 degree angle of incidence the pressure change due to the physical presence of the microphone is fairly small (only 1 dB too high at 10 kHz). Pointing such a microphone towards the source (i.e. under an angle of incidence of 0 degrees) would cause much higher and undesirable pressure increases. Of course, in measuring the noise from aircraft in flyover the dominant sound intensity is in a frequency range much below 10 kHz anyway, and the small deviation in pressure response at and above 10 kHz is of little consequence.

For a "freefield microphones" (such as the B&K type 4133 1/2-inch condenser microphone) the frequency response towards a sound wave impinging under 0 degrees has been adjusted by the manufacturer such that there the pressure increase is electronically compensated for; hence its frequency response is flat up to 20 kHz. Of course, such a microphone would have to be continuously pointed towards the sound source, an inconvenient undertaking for an aircraft in flyover. Hence, again, the pressure response type microphone under a grazing incidence arrangement is to be preferred!

Thus, a microphone is named after its <u>frequency response flatness</u>: a pressure microphone has a flat response for pressure excitation ("under a little cavity") while a freefield microphone is flat for sound impingement at 0° incidence up to its highest usable frequency.

Another important aspect in selecting microphonos relates to the desired frequency range, and dynamic response. Condenser microphones are offered in different diameters, such as 1/10 inch, 1/8 inch, 1/4 inch, 1/2 inch and 1 inch. The small diameter microphones usually have a frequency range that extends to very high frequencies (up to 150 kHz), i.e. well into the ultrasonic range. They are, however, much less sensitive than the larger diameter microphones and generate higher internal noise.

For flyover noise measurements, the audio-frequency range is of primary interest. A microphone's frequency range must therefore normally not extend much above 10 or 12 kHz. Thus, the larger diameter microphones, i.e. 1 inch and 1/2 inch are mostly used. These microphones have a large dynamic range, typically from 10 dB to 145 dB (re $p_0 = 2 \times 10^{-5}$ N/m²) for the 1 inch microphone and from 25 to 160 dB for the 1/2 inch microphone. Due to its smaller physical size, the 1/2-inch-diam. condenser microphone is preferred in measuring aircraft noise.

1/4-inch and 1/8-inch-diam microphones are mostly employed in laboratory or wind tunnel model noise studies, where the frequency range of interest often extends into the ultrasonic regime. It is however not only the actual frequency range that is of importance in this context (aircraft noise has little energy in the ultrasonic range), but rather the extremely fast pressure rise-times that are characteristic for impulsive type sounds. Such impulsive noise typically occurs during helicopter blade-slap or from high-speed propellers. Microphones with an insufficient upper frequency range would tend to clip such an impulsive "needle-type" signal. Those with a wide frequency range extending into the ultrasonic regime are therefore sometimes used when aircraft noise contains impulsive components.

(b) <u>Wind Screens</u>

Microphones in the field must be equipped with windscreens to reduce wind induced noise. Such wind screens, sometimes also called "wind-balls" of 6 to 9 cm in diameter typically provide a 10 dB noise reduction for wind-induced noise for wind speeds within the acceptable range for certification testing.

(c) Dehumidifier

It is also good practice (when using condenser microphones) to employ dehumidifiers, which can be inserted between the microphone-cartridge and the preamplifier. In the course of a typical test day, microphones and other equipment may be set up early in the morning, when humidity tends to be high. Since instrumentation should be switched on at least one hour before the first measurements are made, microphones must be protected from humidity which can condense on or behind the diaphragm. Note that a dehumidifier requires "back-vented" microphone cartridges (not side-vented ones) to allow the chemical agent (e.g. silica gel) to remove detrimental humidity from inside the microphone.

(d) Preamplifier

Directly behind the capacitor of the microphone cartridge or behind the dehumidifier there will be the preamplifier. The main function of a preamplifier is not to provide voltage gain, but to convert the high electrical impedance at the output of the microphone (typically greater than 10^9 ohm) to a low impedance (typically less than 25 ohm). A low impedance is needed to drive long signal cables without significant attenuation of signal amplitude. Preamplifiers are designed so that their physical dimensions match those of the cartridge, combining into one handable unit. Within the design frequency range they are linear, i.e. they do not change the frequency response of the cartridge/preamplifier assembly. A typical 1/2 inch diam preamplifier for use in combination with a 1/2 inch diam cartridge, for example, would be linear between 20 Hz and 20 kHz.

The combination of the wind-screen ("wind ball"), the microphone-cartridge, the dehumidifier, and the preamplifier then constitutes the "microphone assembly", or "microphone" for short (Fig. 3.4).

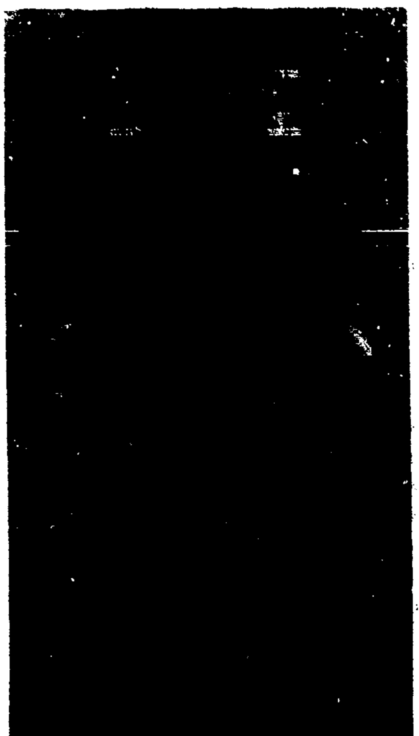


Fig. 3.4 Front Panel of battery-driven 2-channel power supply (B&K type 2804)

(e) Power Supply

Condenser microphones (other than the prepolarized types, see Section 'f' below) must be supplied with a polarization voltage (e.g. 200 V). Also, the preamplifier ("impedance converter") requires its own electric power. For both such purposes, power is usually supplied by an external supply- unit that is connected via a screened cable to the microphone-assembly. Such power supplies can be battery-driven (supplying only one or two microphones, Fig. 3.4) or be connected to the electric main power supply in which case they could feed several microphones (e.g. six or eight) by multiplexing.

An external power-supply is not necessary, or can be bypassed, if the microphone assembly is connected to some measuring instrument that has its own built-in power-supply. Certain types of 'Sound Level Meters' ("SLMs"), 'Frequency Analysers' or 'Measuring Amplifiers' come with power-supply connections so that microphone-assemblies can be connected directly to such equipment.

The power supply unit (or units) would then connect through an appropriate number of cables (one for each microphone) to a tape-recorder (or, as the case may be, to a level-recorder or to some other display unit etc.).

(f) Prepolarised Condenser Microphones (in Combination with Precision Sound Level Meters)

Prepolarised condenser microphones are constructed with a charge-carrying layer on the diaphragm, eliminating the need for external polarisation. Their main advantage is in the power savings in field use (if that is of concern) and they are typically used in conjunction with hand-held precision sound level meters. If - as in noise certification of light propeller-driven aeroplanes - only an $L_{pA,max}$-value is to be determined by visually reading the meter, using a prepolarised microphone is convenient.

The output of such a microphone/sound-level-meter system can also be recorded on a tape-recorder for later laboratory analysis. Prepolarised microphones are usually of the free-field type (rather than of the pressure type); they must, therefore, be actively directed towards the aircraft.

(g) Extension Rod

It is often convenient to attach the microphone-assembly to a flexible extension rod (sometimes called "goose-neck"), which can be mounted on a floor-stand or tripod. It can also be directly connected with a portable SLM. The goose-neck allows a pressure-response type microphone to be easily positioned in the direction of the expected grazing sound incidence. This is particularly convenient for side-line microphones, where the diaphragm must be oriented at some angle with respect to the ground surface plane. Tripod heads, can, of course, also be directed in any desired position for optimum microphone orientation.

The above microphone arrangement refers to the customary position 1.2 m above the ground, as still specified in the ANNEX 16 Chapters 3, 6, and 8. If the microphone must be positioned directly on the ground to eliminate ground reflection effects as required in ANNEX 16/Chapter 10 a special adapter must be used, which places the inverted microphone at the correct distance (7 mm) above the circular hard support plate (see Fig. 2.22).

(h) Extension Cables

The centerline microphone is usually placed fairly close to the data recording station (within 10 to 30 m distance, or so). Sideline microphones as required e.g. for helicopter noise certification are 150 m to each side of the center microphone. This distance can be bridged by extension cables, which typically come in lengths of 3 m, 10 m, or 30 m. Such cables must be well shielded, so that no extraneous signals, as radiated by radio stations, are picked up. (It may be entertaining for the test-engineer to listen to music through his acoustic data acquisition system, but that is certainly not helpful for the original purpose). Even longer distances will have to be overcome, if the signals from several microphones (say at 450 m to both sides of a center-station) must be recorded on the same recording tape. If this is not absolutely necessary, it is certainly less complicated to equip each remote measurement station with its own tape-recorder. In that case, time-synchronisation is imperative, and each measurement station should simultaneously record a common, radio-transmitted, time-code on the data-tape, as will be discussed in Section 3.4.2.

(i) Electric Power Generators

Much of the equipment described above is available in battery- driven versions. Although automobile batteries can sometimes provide low voltage electric power in the field, it is usually better to use a quiet piston- engine powered electric power generator. Such power generators are available in low-noise versions which can be positioned fairly close to the microphones. If many tape recorders, power supplies, analysers etc. must be used in a field where no electric current is available, such autonomous generators are very convenient. Commercial models, supplying, for example, 400 W or 1000 W, are well suited for the subject purpose.

3.2.2 Data Recording

(a) Signal Conditioning (Amplification, Spectral Shaping)

The signal, as it comes from the microphone via the preamplifier requires some conditioning prior to recording. It will have to be amplified and - if necessary - spectrally shaped before it can be recorded on a recorder of limited dynamic range. The microphone signal is usually of the order of milliVolts (sometimes only microVolts) and must be amplified to the voltage required for the tape recorder (usually of the order of 1 Volt RMS). The signal conditioning depends on the original signal strength and on the special characteristics of the acoustic signal (e.g. if it has predominantly low frequencies or predominantly high frequencies, or if the dynamic range is beyond the capabilities of the recorder).

For example, the noise signature of a helicopter under blade slap conditions with substantial impulsive noise components may have a total dynamic range of 90 dB. A typical analog recorder, however, would not be capable of recording such a large dynamic range. In such a case one can spectrally shape the signal by de-emphasizing (attenuating) the low frequency-part with respect to the high-frequency part, thus reducing the dynamic range of the entire signal <u>before</u> recording on one channel. This technique will also be discussed in Section 3.2.3.

Amplifiers with typical gains from 1 to 1000 in conjunction with a band-pass filter (e.g. variable high-pass/low-pass capabilities) could be used for such purposes. A commercially available dual channel filter for instance features a high-pass filter with a variable low frequency cut-off 0.1 Hz to 10 kHz. Such filtering can also be useful in field measurements where wind-induced noise of predominantly low frequency could cause an overloading of the tape-recorder's dynamic range.

(b) Analog Tape Recorders (Direct Mode, Frequency-modulated 'FM' Mode)

In the area of aircraft noise research analog tape recorders are still most widely used, although digital recorders (and moderately prised video-recorders) may eventually replace analog recorders on account of their substantial advantages with respect to dynamic range, linearity, track-to-track phase match and long recording duration.

There are two basic types of recording modes for analog tape recorders: <u>direct recording</u> (DR) and <u>frequency modulation recording</u> (FMR). High quality tape-recorders accept plug-in units which allow all or a number of channels to be converted from one into the other. In the DR-mode, the analog signal is directly recorded on tape, while in the FM recording mode the signal is modulated upon a carrier-frequency; amplitude variations then result in carrier-frequency modulations.

DR and FMR differ in their relationships of tape-speed, achievable frequency range, dynamic response and signal-to-noise ratio. In the DR-mode only AC-signals can be recorded down to a lowest frequency which is a function of tape-speed. A typical analog tape recorder, in the "intermediate band" mode, might have a DR-bandwidth of 300 Hz - 600 kHz at the high tape speed of 120 in/s and one of 50 Hz - 2.3 kHz at the low tape speed of 15/32 in/s.

When operated in the FM-mode, tape-recorders can record from DC, i.e. from 0 Hz up to a highest frequency which again depends on the tape-speed. A typical tape recorder - such as the RACAL Storehorse 14 channel tape recorder (<u>Fig. 3.5</u>) in the intermediate band mode - can record from 0 Hz to 40 kHz at 120 in/s and from 0 Hz to 156 Hz at 15/32 in/s. The benefits of FM recording lie in the good low-frequency phase linearity and the excellent amplitude stability. FM-recording is therefore particularly useful, when acoustic wave-forms ("acoustic pressure time-histories") must be preserved rather than the spectral information.

For flyover noise measurements, where the typical frequency range of interest lies between 50 Hz and 12.5 kHz one could use either the DR-mode at the fairly low tape speed of 3 3/4 in/s (with an

Fig. 3.5 14-channel tape recorder (RACAL Storehorse)

associated frequency range of 50 Hz to 18 kHz and a dynamic range ≙ S/N-ratio of 40 dB). If even lower frequencies are of interest, such as for certain types of helicopters, one would employ the FM-mode at a tape speed of 30 in/s to allow recording from 0 Hz up to 10 kHz (S/N-ratio of 52 dB), or if necessary of 60 in/s to record up to 20 kHz (S/N-ratio of 52 dB).

Clearly, the recording mode and tape-speed to be employed largely depend on the frequency range of interest and the dynamic range of the signal to be measured. In field use, tape consumption may also be an important issue (apart from cost-aspects): if a slow tape speed can be used, tape changes are less frequent - a distinct advantage, since any such change constitutes a test-disruption and requires a new tape calibration. On the other hand, if high quality data at relatively low frequencies are required - as for instance in helicopter noise research - the FM-mode and a high tape speed must be used, e.g. 60 in/s. To give an indication of tape-use: a typical 15-inch tape reel would run through the recorder in about 20 minutes at that tape-speed.

In a typical noise-certification test for subsonic jet aeroplanes between 6 and 8 microphones would be a minimum required for the take-off/sideline noise data acquisition. If, in addition, microphones at different heights above the ground are employed (as becomes quite common now in aircraft noise research) to compare the signals from e.g a microphone at 1.2 m above ground and one directly on the ground surface, even more microphones must be employed. In that case a multi-channel tape recording is absolutely necessary.

If a smaller number of microphones suffices, as in a standard helicopter noise certification where only 3 microphones are specified, high quality tape-recorders with fewer channels can be employed, such as the battery-driven and portable B&K 4-channel (type 7005) or the RACAL 7-channel (type STORE 7 DS) analog tape recorders (Figs. 3.6 and 3.7). They may be operated in either the FM-mode or the DR-mode by means of plug-in FM-units or DR-units. These instruments allow recordings from DC up to 15 kHz at 15 in/s in the FM-mode. In the DR-mode recordings from 20 Hz to 6 kHz at 1.5 in/s, or from 35 Hz to 75 kHz at 15 in/s are possible. (These lower and upper bound frequencies are defined by the respective -3 dB points!).

Fig. 3.6 4-channel tape recorder (B&K type 7005)

A tape recorder must provide at least one voice (or cue) channel for annotation purposes. Many tape recorders feature an extra voice-track (usually at the edge of the tape) with less dynamic and frequency range than the measuring tracks. On such special tracks a continuous time-code or time-synchronization (square wave) pulses can also be recorded.

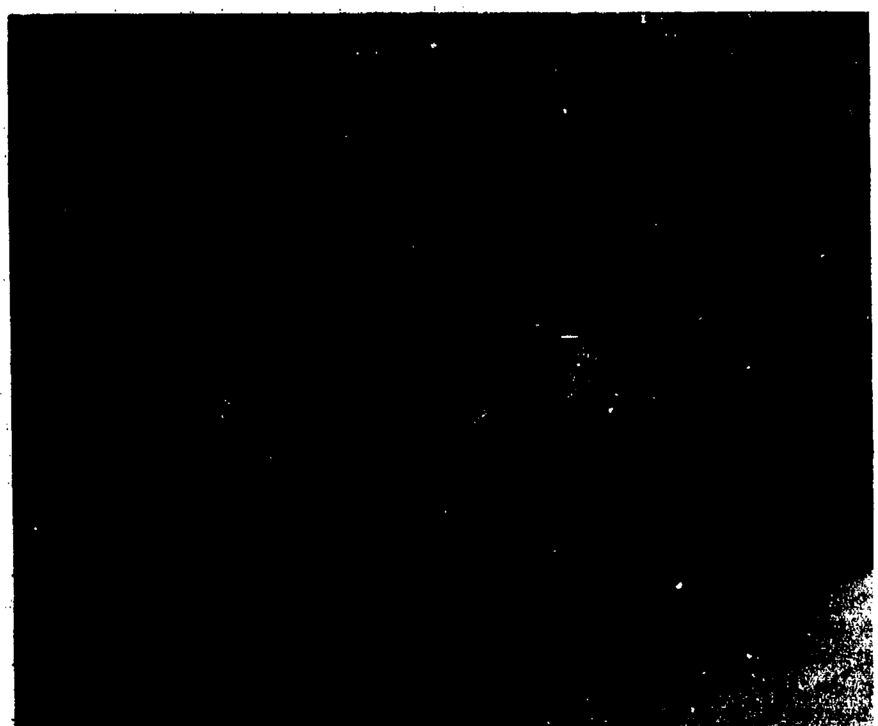


Fig. 3.7 7-channel tape recorder (RACAL Store DS 7)

Tape-recorders with 2 channels can also be used in aircraft noise certification where only one microphone is required, as in light propeller-driven aeroplane noise certification. Autonomous measurement stations could then each use a separate 2-channel tape recorder, such as the NAGRA type IV-SJ (Fig. 3.8).

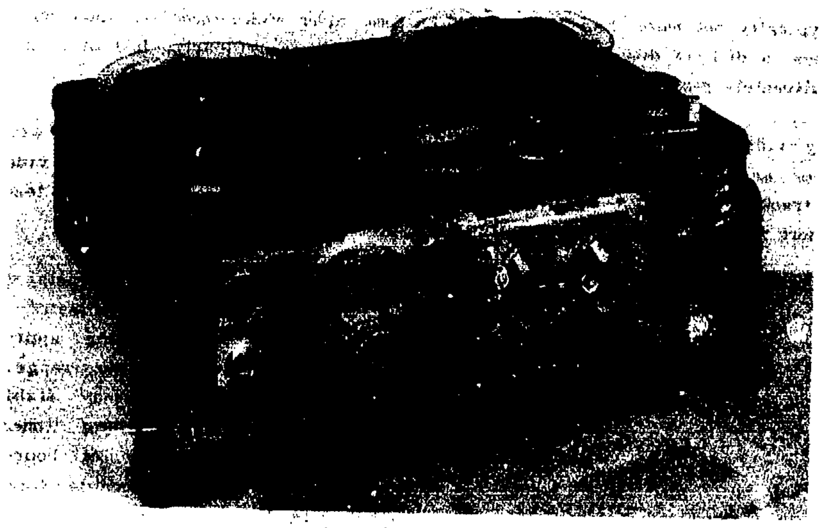


Fig. 3.8 2-channel tape recorder (NAGRA type IV-SJ)

(c) Digital Tape Recorders, Video-Recorders, Pulse Code Modulation Technique

If flyover noise data are to be evaluated in terms of EPNL using a computer, it is convenient to store data as obtained in the field directly in digital form, ready for computer-processing. This would eliminate the intermediate step of acquiring/storing the data in analog form first, as - before processing - data would have to be converted to digital data, anyway. An example of an appropriate direct digital recorder is the TEAC RD-101-T (Fig. 3.9). One could make use of "the best of both worlds" by employing one channel of an analog multi-channel tape recorder for digital storage of very low frequency (non-acoustic) information, such as atmospheric data (humidity, temperature, air- pressure etc.) or some time-code, while using the other channels in their FM-mode for the acoustic data.

Fig. 3.9 Digital recorder (TEAC RD-101-T)

Better results than possible with direct recording or FM-recording of analog data can be obtained by recording digital data on analog tape recorders. In that case the analog signals must first be converted to digital data by means of an appropriate Analog/Digital-Converter such as the Nakamichi DMP-100 which employs pulse code modulation 'PCM'; this is a 2-channel unit that can accordingly feed 2 tape-channels.

Digital data recording provides excellent frequency-linearity within the required frequency regime. PCM digital data can be stored on a normal analog tape-recorder and played back through a Digital/Analog- Converter to supply the original analog data for further processing if necessary. PCM digital data can also be recorded on commercial video-recorders. Because of the high bit rate, which video-recorders can accept (on account of their rotating record/reproduce-heads), they have a large dynamic range of typically 90 dB. This is substantially better than that of any analog recorder (with typically not more than 40 to 50 dB). Some older video-recorders, however, show high drop-out rates, a distinct disadvantage in acoustic data storage. Clearly, loss of even only a few 'bits' can ultimately result in erroneous levels.

High quality video-recorders (such as from the SONY U-Matic series, Fig. 3.10) with improved error-detection and correction capabilities must be preferred, therefore. To-day's video-recorders use only 2 tracks, which fact may present a limitation in acoustic flyover noise testing, where frequently more than 2 channels are required.

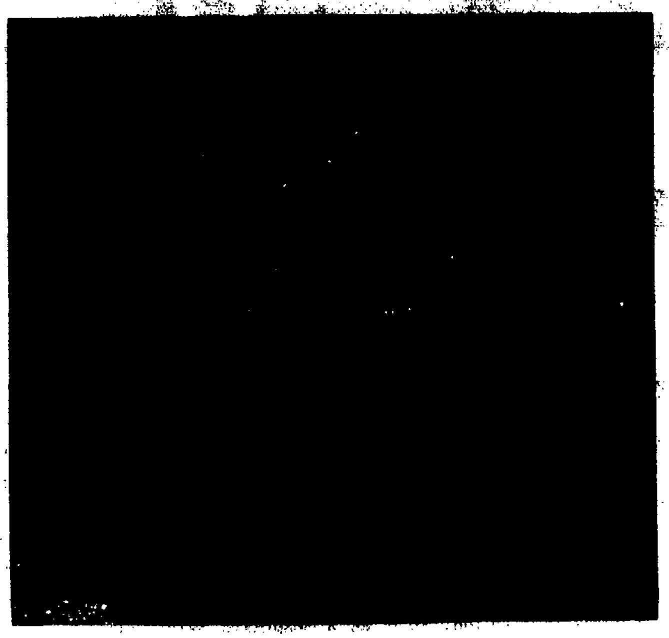


Fig. 3.10 Video recorder (Sony U-matic)

The advantages of the PCM-processor/ video-recording approach (wide dynamic range, excellent frequency stability, long recording times in the order of hours at very reasonable tape consumption) are counteracted by a severe disadvantage for acoustic data storage: the limited frequency range of typically only 1/4 of that of an FM-recording. Depending on the number of channels used, the upper frequency limit may be only a few kHz (typically 1 to 3 kHz).

Low-price PCM-processors must be started and stopped by hand, which is inconvenient. There are, however, other high quality (and high price) multi-channel audio-studio digital recorders with built-in PCM-processors for all channels, such as the 24-digital-channel/ 4-analog-channel SONY type PCM-3324 (Fig. 3.11) with stationary record/reproduce heads. This instrument combines high dynamic range (in excess of 90 dB) with a sufficiently wide frequency-range (20 Hz to 20 kHz +0.5/-1.0 dB), requiring however high tape speeds.

If dynamic range is not the overriding issue in a test, the "conventional" analog tape-recorder in its FM-recording mode may still be the best instrument for aircraft noise measurements.

3.2.3 Data Monitoring and Instrumentation Considerations

(a) Clipping

In actual field testing, acoustic data - as received from the microphone - must be checked before they are stored. It is useful to monitor incoming signals before recording. This can be done by visually observing either the pressure-time traces on an oscilloscope or the voltage- (i.e. level-)

indicator on a measurement amplifier or an indicating (precision) sound level meter. This practice helps to check for clipping or overloading, since the gain of the preamplifier must be properly set to assure that undistorted signals are acquired.

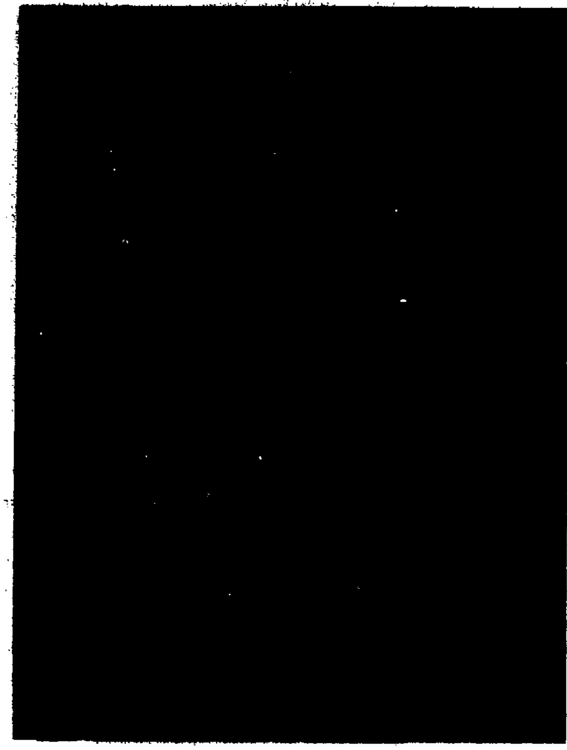


Fig. 3.11 24-digital-channel/4-analog-channel recorder (Sony type PCM-3324)

Impulsive-type noise signals are particularly sensitive to clipping. As discussed before, the signal as coming from a microphone must often be filtered to adjust its dynamic range to comply with the dynamic range of the recorder. The gain after filtering is now dictated by the original signal to ascertain that it is recorded within the optimum regime of the recorder. Suppose, for instance, that the noise of a helicopter with blade slap must be recorded. For the direct-recording NAGRA IV SJ recorder (see Fig. 3.8) the 3-dB-distortion- point lies approximately 6 to 8 dB above the 0-dB-mark ("full-scale mark"). For such an impulsive-type signal the amplification should be set so that the indicator needle remains between 5 to 10 dB below this full- scale mark. This practice would provide a 10 to 15 dB margin above the expected full-scale signal. On the subject NAGRA instrument the time constant of the indicator needle is (deliberately) rather long; although this instrument does read "peak"- values, it cannot, therefore, indicate short duration impulses. If during a flyover event the indicator needle would show a "peak"- value of -5 dB below full scale, there may still be impulsive peaks well in excess of that indication. By providing an ample overload margin, clipping is prevented and the impulsive type signal is not distorted during recording.

This is certainly an extreme case and several other types of aircraft noise, where there are few or no impulsive components (such as broadband jet noise and low-speed-propeller noise) do not require such an overload precaution. As stated earlier, it is good practice to monitor all microphone signals <u>prior</u> to filtering to obtain an indication of their possible impulsive character (crest-factor). <u>Fig. 3.12</u> shows time histories of a highly impulsive type signal from a helicopter flyover, and a fairly broadband signal from a jet aeroplane flyover to illustrate these two borderline cases.

(b) <u>Dynamic Range Considerations</u>

Allowing an extra safety margin in the gain setting, however "eats heavily" into the available dynamic range of the recorder. In critical cases it might be useful to employ a second channel for recording the same signal with a different gain setting if the original signals have a dynamic range in excess of that of the recorder.

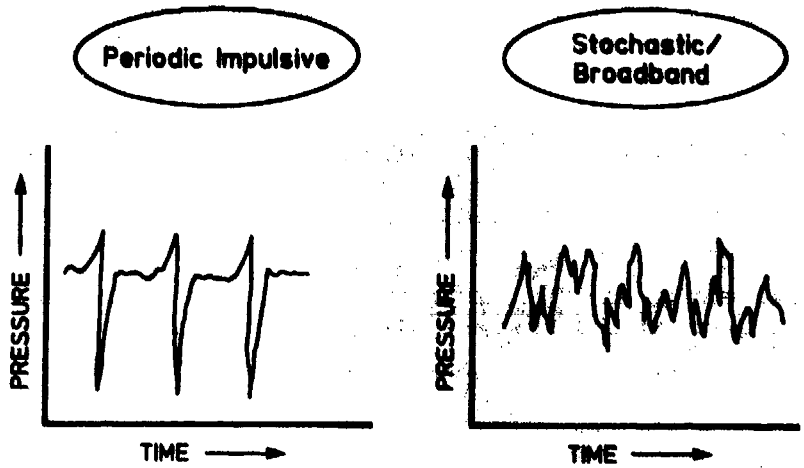


Fig. 3.12 Typical pressure time histories for periodic/impulsive and stochastic/broadband noise

Suppose, a helicopter signal must be recorded, where most of the acoustic energy is in the low frequency region and where the signal had a dynamic range of 90 dB. While microphones, preamplifiers and signal conditioners can readily cope with such a wide range, a typical analog tape recorder cannot. The signal could then be spectrally shaped by de-emphasizing the low frequency portion before recording. Alternatively, when using a 2-channel tape recorder one channel could be used to record the signal as is (with the appropriate amplification). and in the other channel a low-frequency-roll-off filter could be inserted, again using the appropriate amplification. Although the second signal would be distorted in its low-frequency region the high frequency portion would now be well above the electronic noise floor of the tape-recorder.

(c) Filter Phasing

Employing such a pre-emphasis filter on one channel destroys, however, the phase relationship! For an ideal filter, the relationship between phase and frequency should be linear; a passive (analog!) filter usually does not meet this requirement. If the filter had a roll-off frequency of, say, 1 kHz, then the phase at 4 to 5 kHz will not be linear anymore with frequency. Hence, when the interest really was in the (time-dependent) wave-form then any time-domain-related information would be lost. The phase information, however, would still be available on the other channel (where no filtering took place).

A (direct recording) tape recorder has its own low-frequency roll-off, perhaps at 20 Hz, thus acting as a filter by itself. It would thus affect the phase-relationship of the recorded signal up to perhaps 200 or 300 Hz. Phase destruction is inherent. One therefore must employ FM-recorders, which record from DC on, if one is interested in the wave-form of a predominantly low frequency acoustic signal. In this case, one would also use a signal conditioning amplifier with a correspondingly lower roll-off frequency of e.g. 1 Hz. Such an amplifier would affect the phase only up to 5 or 10 Hz. Even for a helicopter noise signature - with substantial acoustic energy at frequencies as low as 20 Hz - such recording would now be suited for acoustic wave-form analysis.

Choice of the filtering and recording, therefore, depends on whether the interest is in the frequency-domain (spectra) or in the time-domain (wave form). In aircraft noise certification the information of interest is only in the frequency domain since either the overall A-weighted sound pressure level or the band-pressure levels in 1/3-octave-bands is required. In the frequency domain a phase-shift introduced by a filtering has no effect; thus one can safely employ DR-tape-recorders, provided their lower frequency roll off frequency is sufficiently below the expected signal frequencies.

(d) Graphic Level Recording

Flyover noise data are usually analysed off-line in the laboratory. It is useful, however, for the test engineers in the field to have a "quick-look" possibility to verify whether the data, as sent to the recorder, are valid. One might thus wish to monitor the output of each microphone not only on the oscilloscope-screens, but also employ graphic level recordings to have an instant record of the (e.g. A-weighted) flyover noise time history. This not only provides an ad-hoc feel for the data, while they are taken; but also helps to detect "unexplainable" differences in the levels from side-line microphones or to identify other unrelated acoustic disturbances. Suitable graphic level re-corders for this purpose are the B&K type 2317 (single channel) or the B&K 2309 (dual-channel) (Fig. 3.13). These recorders accept different potentiometers, ranging from 10 to 75 dB. In flyover noise testing a 50 dB potentiometer is usually appropriate for the typical ratio of useful signal and ambient noise floor. If more than one or two microphone signals must be monitored, then multi-channel graphic level recorders can be used.

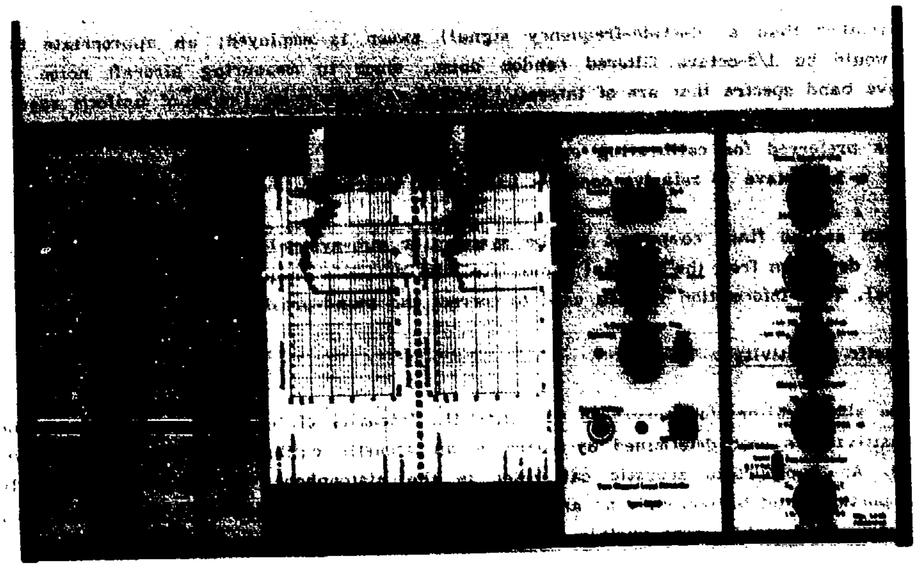


Fig. 3.13 Dual-channel graphic level recorder (B&K type 2309)

3.2.4 Calibration

Prior to testing, it is necessary to calibrate the acoustic measuring system to determine both its frequency response over the entire frequency range of interest (e.g. 20 Hz to 12.5 kHz) and its acoustic sensitivity.

(a) Frequency Response

Frequency response calibration serves to determine deviations of the entire recording/reproducing system from an ideal uniform frequency response. In noise certification testing such calibration would best be done in 1/3-octave bands. The calibration of a system can be executed in one of two ways: (1) either an overall calibration is made (i.e. from the microphone all the way through to the final analyser out-put), or (2) each of the major subsystems (e.g. preamplifier, power supply, signal-conditioner prior to the recorder input as one sub-system, and the recording system through the analysis system as the other sub-system) is individually calibrated. In the latter case, the calibration signals are inserted at the input of each sub-system and the output is obtained at the last component of the sub-system. The electrical response of the entire system is then the arithmetic sum of the individual responses from each sub-system.

Before determining the system response, the pressure response of any microphone can be obtained by means of an electrostatic actuator, employing for example a reciprocity calibration apparatus (e.g. B&K type 4143) in conjunction with an adapter (B&K type UA 0023). When applying an appropriate sine-signal to the actuator, the resulting electrical field will move the microphone diaphragm in a way similar to an acoustic signal, providing the frequency response of the microphone itself. Frequently, however, the manufacturer's calibration sheet on microphone sensitivity is accepted, since only mechanical damage of the diaphragm or some gross mishandling could alter its frequency response.

The system-response is obtained by feeding an electrical signal from a sine/random-noise generator to the microphone-preamplifier from which the microphone cartridge has been removed. The signal is then swept through the frequency range of interest. In noise certification testing a broad-band signal (rather than a discrete-frequency signal) sweep is employed; an appropriate broadband signal would be 1/3-octave filtered random noise, since in measuring aircraft noise it is the 1/3-octave band spectra that are of interest. Instead of white noise (noise of uniform spectral density ≙ absolute constant bandwidth), pink-noise (white noise fed through a -3 dB/octave filter) is sometimes preferred for calibrating an acoustic measurement system, since it provides a uniform level for a 1/3-octave (≙ relative constant bandwidth) representation.

The output at the final component of the system (or sub-system) then constitutes the frequency-dependent deviation from the original input, i.e. the system's frequency response to any given input signal. This information is then used to correct the sound-pressure band levels.

(b) Acoustic Sensitivity

While the above calibration serves to determine the linearity of the frequency response, the absolute sensitivity is best determined by means of an acoustic calibrator generating a known sound pressure. An appropriate acoustic calibrator is the pistonphone. Pistonphones (being light in weight, portable and battery-driven) are held on top of the microphone-cartridge, where they generate an extremely stable, reproducible and constant sound pressure level of e.g. 124 dB at 250 Hz. There are other types of pistonphones that operate at 1000 Hz or at other preset frequencies and adjustable levels. It suffices to check the acoustic sensitivity at one frequency only, as the frequency response is already known from the calibration procedure described above under (a).

(c) Insert Voltage Frequency Calibration

In field testing, where a substantial number of microphones is used that are often located at large distances from the central measuring station, it is advisable to use the insert voltage calibration technique. This is a convenient method for remotely field-checking the electrical sensitivity of a complete sound measurement system, including preamplifiers and cables. The method does, however, not account for the mechanical parameters which determine the acoustic properties of the microphone cartridge itself.

A special preamplifier such as the B&K type 2645 for a 1/2 inch diam microphone cartridge is then inserted between the microphone cartridge and the power supply; the power-supply is connected to the preamplifier input socket of a measuring amplifier or a frequency analyser of a type that can supply an insert voltage (e.g. the B&K measuring amplifier type 2636). It is also possible to use an external sine-generator with variable frequency and voltage output. The entire frequency and level calibration of the measuring system ("downstream" of the microphone cartridge) can then be done remotely, eliminating the need to perform individual pistonphone calibrations on each microphone.

(d) Measuring-Instrument Detector/Indicator Characteristics

The calibration-procedures discussed so far apply to continuous signals. Aircraft flyover noise is, however, inherently transient in nature and sometimes highly impulsive. In these cases the detector/indicator characteristics of the metering instrument must be well understood in order to correctly interprete the signal observed.

Sound level meters (SLMs) are usually equipped with several preset response characteristics, e.g. termed 'impulse', 'fast', and 'slow'. These designations refer to the speed with which the indicator-needle on the metering instrument (the "scale") approaches a maximum value. The critical parameter is the 'time-constant' of the 'exponential* averaging circuit' in the instrument; these time constant - in "precision SLMs" - are 35 ms, 125 ms, and 1000 ms for the detector responses 'impulse', 'fast', and 'slow', respectively.

If a (tonal) sound burst is applied to an SLM, the needle will start deflecting. But before it has reached the deflection that would correspond to the maximum signal level, the burst has ended and the needle will fall back again. The speed at which this happens is a function of the duration of the tone-burst t_i and of the detector time constant τ . The number of deciBels Delta L by which the needle "fails" to reach the maximum can be calculated from

$$\text{Delta L} = 10 \log ((1 - \exp(-t_i / \tau))$$

For example, if a tone burst of 200 ms duration is applied to the SLM set at the detector-response 'fast', the needle would come up to 1 dB of the maximum level; if the detector-response was set at 'slow', it would miss the maximum by 7.4 dB.

Aircraft do not emit single tone-bursts, but "sequences of tone-bursts" (repetitive sound events of short duration) which for a helicopter under a blade-slap condition would translate into a periodic emission of impulses of identical wave-forms. A four-blade helicopter with a main-rotor speed of 400 RPM will, for example, emit 20 impulses per second, each perhaps only 10 ms long. The sound level meter will then show an average needle-indication, several deciBels below the maximum sound level during the pulses.

The amount Delta L, by which the needle misses the maximum sound level is again a function of the detector-response time constant and the burst duration (or some characteristic time duration of the individual impulse-signal), but now also of the repetition rate of the bursts T, given by

$$\text{Delta L} = 10 \log (((1 - \exp(-t_i / \tau))/((1 - \exp(-T/ \tau)))$$

These dependences are illustrated in Figs. 3.14 and 3.15.

It is therefore necessary to specify the detector-response characteristics of the sound level meter that is used to measure aircraft flyover noise levels. ANNEX 16 specifies a "slow" setting of SLMs (or equivalent measuring amplifiers) in all cases. This is not wrong, even for impulsive type sounds, as long as it is understood that the levels obtained depend strongly on the particular time constant selected; naturally, a 'slow'-reading produces lower levels than if a 'fast' or an 'impulse'-reading was taken. But if one agrees on one particular setting, then all aircraft of a certain type are treated equally.

This last statement is not entirely true, since impulsive type sound signatures are also characterised by their crest-factor. The crest-factor is the ratio of the peak sound level to the root-mean-square value of a wave during a given period of time. A very steep needle-type wave-form

* exponential averaging refers to the fact that averaging occurs continuously, i.e. is up-dated all the time. In contrast, linear averaging refers to averaging during a preset time interval

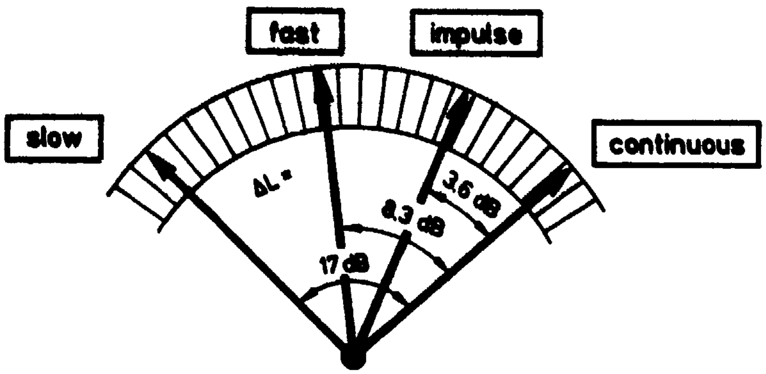


Fig. 3.14 Response to a 20 ms tone burst at various detector time constants 'impulse', 'fast', 'slow'

has a higher crest factor than a sine-wave. Therefore, certain limits have been specified for precision-SLMs: the error must be within +/- 1 dB for a crest factor of 10.

An instrumentation chain must therefore not only be calibrated for its frequency-response and the acoustic sensitivity, but also for its response characteristics to impulsive sound, especially if helicopter noise or propeller-aircraft noise of predominantly impulsive nature is expected. Accordingly, individual tone bursts at several frequencies (e.g. 100 Hz, 1000 Hz) and of different time- duration (e.g. 20 ms, 200 ms) should be applied at certain repetition rates (e.g. 20 Hz, 50 Hz, 100 Hz) to the system and the response characteristics determined.

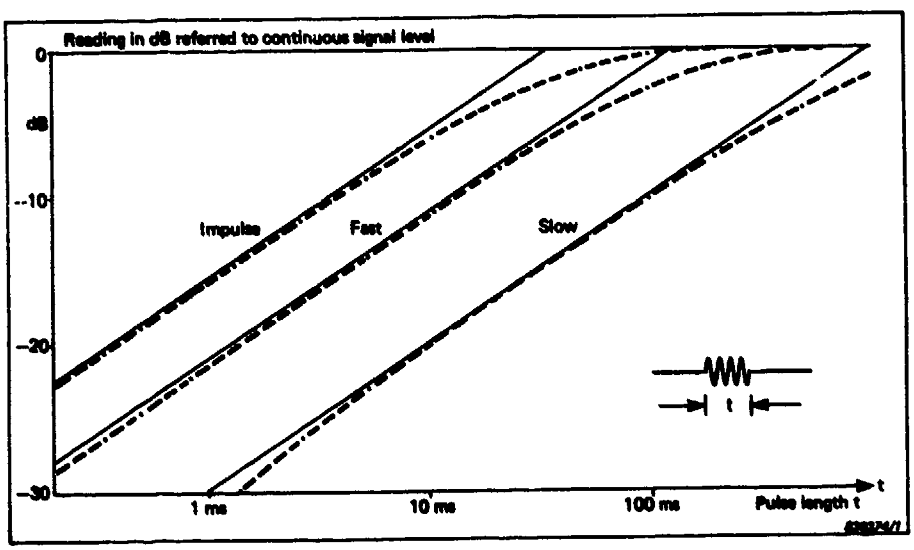


Fig. 3.15 Response of rectifier to tone burst of varying duration

In addition, one might want to check the measurement system for its response towards single-cycle tone bursts, again by comparing the input signal to the final signal output after recording and processing. Within a careful study |6| it was demonstrated that a single low-frequency (e.g. 80 Hz) tone burst consisting of one sine-wave becomes highly distorted when recorded on a direct-record tape-recorder (see also Section 3.2.3 above). No such precaution is necessary when the FM-mode is used or if only spectra and overall levels are required, rather than the exact wave-forms.

3.2.8 Data Analysis

It is good practice to decide already in the preparatory phase of a test on the particular analysis instrumentation to be used. Several aspects must be considered: If a Chapter 6 or a Chapter 10 test is to be conducted, the "end-product" is the maximum overall A-weighted sound-pressure level (acquired with the instrument detector time constant 'slow'). This value can be readily obtained by means of an appropriate **precision sound level meter** (PSLM). Since these instruments are portable and usually provide a digital read-out, the most important values can be read on-line in the field. For a more extensive data analysis using the taped information in the laboratory, such a precision sound level meter can also be used there and no further equipment is required.

The IEC-Publication 651 deals specifically with "Sound Level Meters" and their electro-acoustic characteristics, IEC-Publication 179 with "Precision Sound Level Meters. ANNEX 16, in specifying sensing, recording and reproducing equipment refers to these IEC Publications.

Although not presently required in any of the ANNEX 16 noise certification procedures, one of the ICAO-CAEP member-countries certificates ultralight-aeroplanes in terms of a time-duration corrected A-weighted sound level, the Sound Exposure Level, SEL (or $L_{p,AE}$). The SEL is defined as the constant level which - if maintained for a period of 1 second - would have the same acoustic energy as the (transient) A-weighted measured one-time noise event, i.e.

$$(\text{SEL} \hat{=})\ L_{p,AE} = 10 \log \frac{1}{T_0} \int_{t_1}^{t_2} 10^{L_{p,AE}(t)/10}\, dt$$

Actually, in this particular noise measure the time duration during which the sound was within 10 dB of its maximum value is accounted for. It is argued that slow aircraft with a correspondingly long "exposure time duration" would cause more annoyance, than fast ones.

An SEL-measurement can in principle be conducted over any time span (e.g. over a number of fly-overs), although in aircraft noise certification only the single event is taken into account. SEL-values can again be readily obtained (on-line and in the field) by means of (portable) **integrating precision sound level meters.**

If however a Chapter 3, Chapter 5 or Chapter 8 noise certification test is to be conducted, where the "end-product" is the EPNL, then data must be recorded for later processing and no on-line EPNL readout is possible. While the transient flyover event with respect to a Chapter 6 or Chapter 10 procedure only calls for one (maximum) sound level, the computation of an EPNL requires the acquisition of complete 1/3-octave band spectra every 1/2 second during a time period where the signal is within and below 10 dB of the maximum tone-corrected perceived noise level, i.e. over a time period that may extend over at least 15 to 30 seconds. An appropriate analyser must therefore be capable of storing and processing continuously and in real time the transient flyover event over a sufficiently long time period. Hence a **real time analyser** is necessary; of course, only the recording in the analyser's memory must occur in real time, while the analysis as such can be performed after the signal has been recorded.

There are two kinds of (rapid) real time analysers producing a complete spectrum in parallel bands and displaying it on a continuously updated screen: the **digital frequency analyser** produces 1/3-octave band (or 1/1-octave band) spectra i.e. spectra with constant relative (logarithmic) band-widths, while the **FFT narrow band spectrum analyser** produces narrow-band spectra with constant absolute band-widths.

As stated above, for purposes of a Chapter 3, 5, and 8 noise certification, a succession of 1/3-octave bands is required, and hence the spectral resolution of 1/3-octaves of the digital frequency analyser suffices. If however a more sophisticated and perhaps rather more complex research type flight-noise measurement program is undertaken, where certain discrete frequency sources - though of transient nature - must be identified, then FFT real-time narrow band analysis would be indicated.

The characteristics of some of the above data analysis instruments will be briefly described in the following:

(a) Precision Sound Level Meters

The typical precision Sound Level Meter (such as the B&K type 2235) used in the field as the indicator instrument for flyover noise events has a large stepwise adjustable dynamic range; this range may extend from 24 dB to 130 dB. Also, several detector time constants (sometimes referred to as 'time-weighting'), specifically 'slow', 'fast' and 'impulse', can be selected. The instrument has a built-in frequency weighting network (A-weighting) and is capable of resolving levels to within 0.1 dB (a resolution necessary for aircraft noise certification). A digital display and a maximum hold provision allows a direct readout of the maximum flyover noise level. Some SLMs can be used with both unpolarized and pre-polarized microphones, since they are equipped with an internal polarization voltage source. Usually, the microphone-cartridge/preamplifier-assembly can be removed from the SLM, thus allowing use of an extension cable, if the microphone station is some distance away. The output from the instrument can be fed into a tape-recorder. Several types of B&K SLMs are shown in Fig. 3.16.

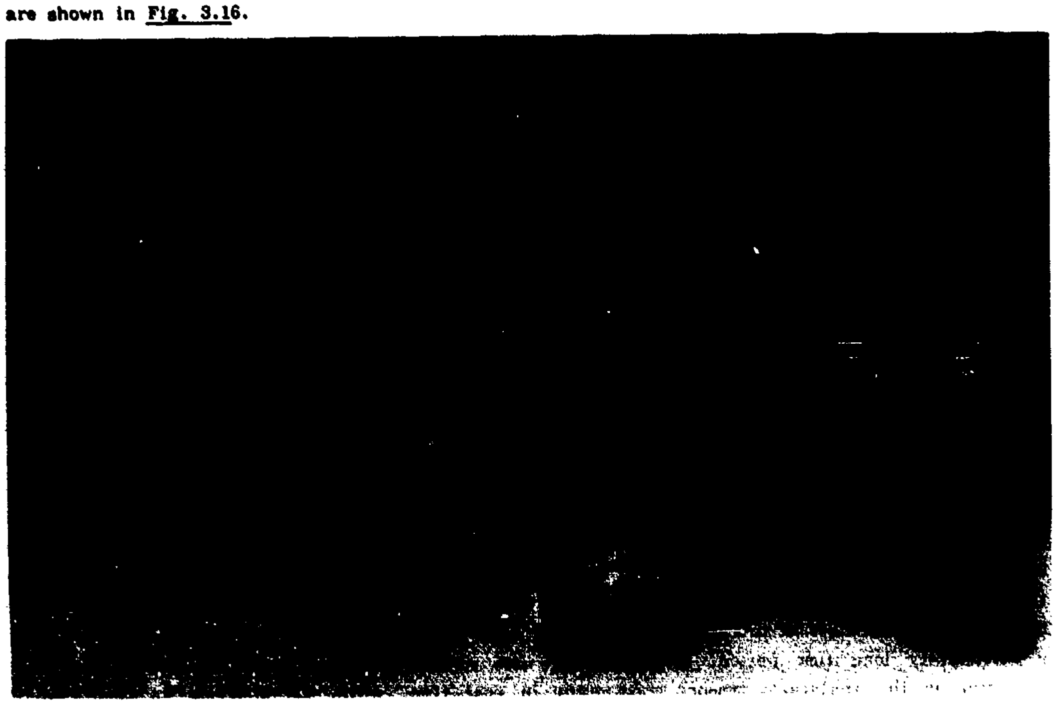


Fig. 3.16 Several types of Sound Level Meters (B&K)

(b) Integrating Precision Sound Level Meter

If a 'Sound Exposure Level' (SEL) is desired in measuring the flyover noise (at present not required in ANNEX 16, as stated before) then a precision Integrating Sound Level Meter (ISLM) would be needed. An instrument such as the B&K ISLM type 2230 has the same features as the SLM described under (a) above, but has additional internal time integration capabilities, which allow the measurement and display of the unweighted or A-weighted Sound Exposure Level.

(c) Measuring Amplifier

While both the SLM and ISLM can be used in the field for real time data acquisition, they can also be used in the laboratory to analyse taped data for $L_{pA,max}$ or SEL. In the laboratory there are usually measuring amplifiers available (such as the B&K type 2610 Fig. 3.17). Such amplifier also has a built-in A-weighting and 'slow' and 'fast' time constants. Use of such an instrument may, however, be an "overkill", since it is really a very sophisticated laboratory instrument with measurement capabilities well in excess of what is necessary for aircraft noise studies.

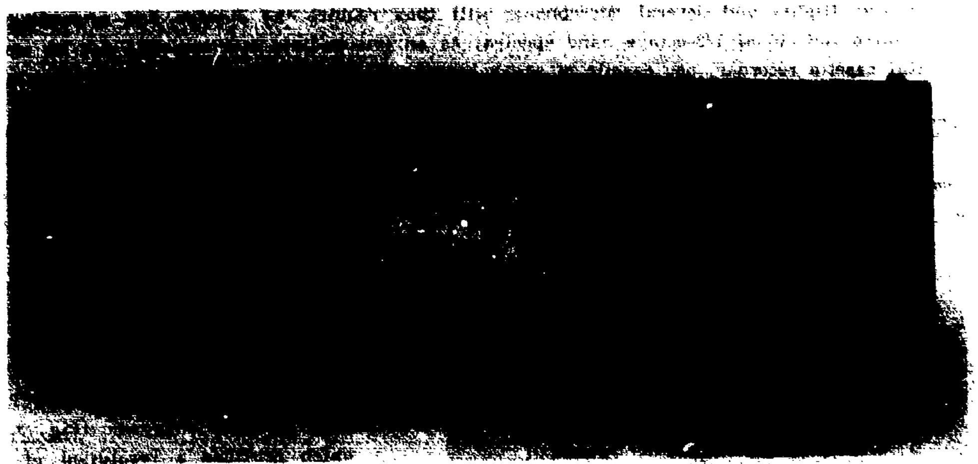


Fig. 3.17 Measuring amplifier (B&K type 2610)

(d) Digital Filtering Real Time Frequency Analyser (1/3-octave Band Analysis)

A suitable laboratory-type instrument for transient flyover noise data reduction is the digital filtering real-time analyser (RTA), such as the B&K type 2133 (Fig. 3.18). This particular analyser features 42 1/3-octave band channels from 1.6 Hz to 20 kHz allowing both linear and exponential averaging and an internal A-weighting network. Such A-weighting would be of special interest only in a Chapter-6 or a Chapter-10 type measurement.

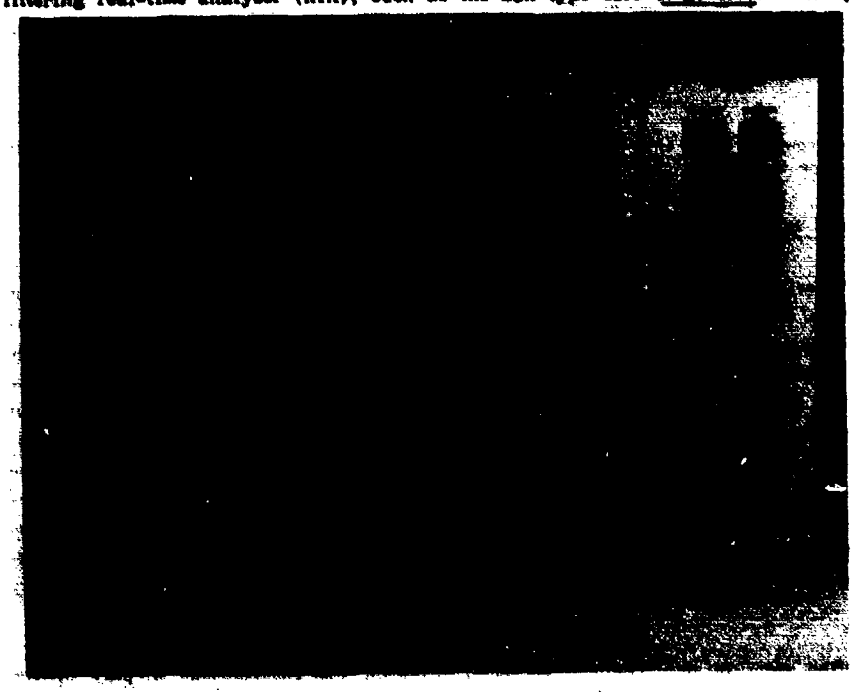


Fig. 3.18 Real time analyser (B&K type 2133)

For the EPNL-computation the "noy-weighting" of the successive 1/3-octave spectra is required, as outlined in Appendix A to this AGARDograph. Since averaging-times (both linear and exponential) may be freely selected between 1/32 second and 128 seconds (in binary steps), a flyover may be observed on the display-screen in real time (in the field or from the tape in the laboratory) at, say, 1/2-second time intervals to obtain a feel for the speed with which the spectra change. The digitally stored 1/3-octave spectra at 1/2-second time intervals can also be transferred to a computer for EPNL-calculations.

A typical flyover can produce as many as 30 to 60 individual 1/3-octave spectra. A whole test with at least 6 test flights and several microphones will thus require the storage and processing of several hundred individual 1/3-octave band spectra. As an intermediate step the data can be stored on a digital casette recorder, one casette of which could easily hold more than 1000 such spectra.

(e) <u>FFT Narrow Band Real Time Spectrum Analysers (Narrow-band Analysis)</u>

Real-time narrow-band analysis is often used in flyover noise studies to observe rapidly changing discrete frequency components in the noise spectrum while the event occurs. Again linear or exponential averaging can be employed to obtain (or display on the screen) the instantaneous spectrum over short or long time-spans within the flyover event. An appropriate instrument for this purpose would be the B&K type 2033 'Fast Fourier Transform Narrow-band Real Time Spectrum Analyser (Fig. 3.19) which provides a resolution of 400 lines in different frequency-ranges (from 0 to 10 Hz, up to 0 to 20,000 Hz). In this case the bandwidth corresponds to the ratio of the upper frequency limit and the resolution (e.g. for a frequency range of 0 to 1600 Hz the constant absolute analysis band-width would be 4 Hz). Such an instrument is not required for noise certification but is often used in basic aeroacoustic studies.

Fig. 3.19 FFT narrowband real time spectrum analyzer (B&K type 2033)

(f) <u>FFT Spectrum and Waveform Analysers</u>

In most certification tests (and noise research in general) real-time analysis is not required. For off-line data reduction an 'FFT-Spectrum and Waveform Analyser' is then a very versatile instrument. Appropriate analysers are the NICOLET model 446B, the SOLARTRON 1200 Signal Processor, the IWATSU Electric Co. SM-2100 Signal Analyser, or the HP-3582A (Fig. 3.20). These instruments are ideal for the analysis of steady-state (stationary) sound events as they occur in noise testing of aeroplanes on the ground, in noise studies with wing-mounted microphones in flight or in aeroacoustic wind-tunnel studies. These analysers can also be used to analyse transient noise in the time domain, where they can reproduce the wave-form of the noise over predetermined time increments (from a few milliseconds for a wide frequency range to several minutes in a very narrow frequency range). Waveforms may be held and subsequently spectrally analysed in 1/3-octave (or 1/1-octave) bands or in narrow bands with a resolution that again depends on the selected frequency range.

These instruments often come in dual-channel versions, allowing the simultaneous display of two events on the screen. A typical instrument might have a frequency range from 0 to 20.000 Hz, while

Fig 3.20 Waveform Analyser (Hewlett Packard Model 3562A)

another one might cover a range up to 100.000 Hz, with resolutions of typically 400 lines starting at a range from 0 to 1 Hz up to 0 to 100.000 Hz, with steps in between. Thus an optimum range for the purpose at hand can be selected.

(g) Plotters

To obtain a hard copy of spectra or wave forms, as analysed and displayed by means of the above discussed analysers, XY-plotters can be used which provide annotated graphic plots of frequency spectra and/or time functions. Such plotters generate one plot of given x- and y-extent, such as individual spectra within a predetermined frequency range or a waveform within a predetermined time span. There are many makes of XY-plotters available, which differ in handling convenience, plotting speed and resolution. Plotters, such as the B&K type 2308 (Fig. 3.21) and type 2319, or the HP-7550A are high quality laboratory type instruments.

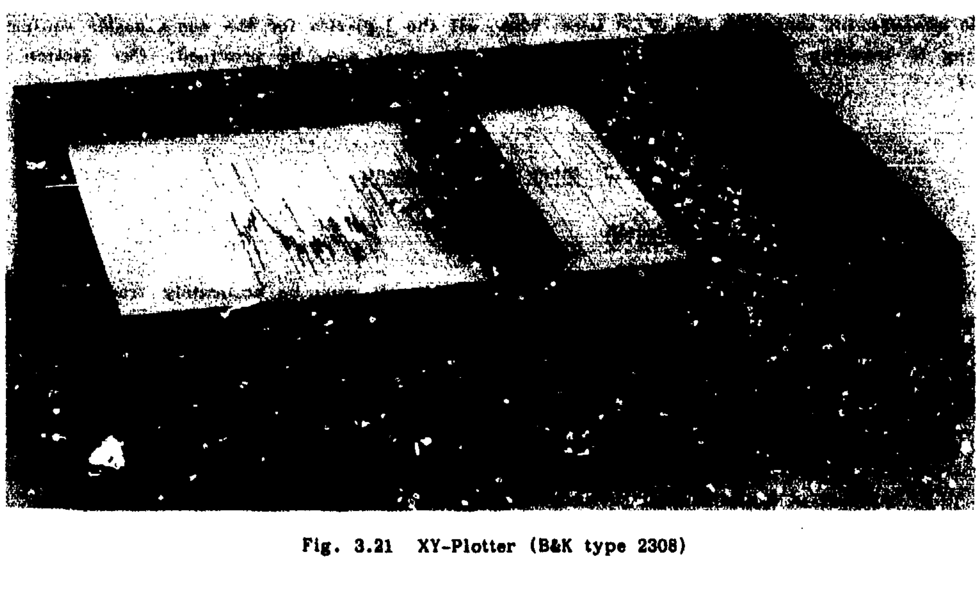


Fig. 3.21 XY-Plotter (B&K type 2308)

To graphically monitor flyover time histories, such as the time-dependence of the A-weighted noise level of an overflying aircraft, continuously operating graphic level recorder are more useful than XY-plotters. They produce continuous time histories on a paper-roll. They usually feature exchangeable dynamic range potentiometers (10 dB to 75 dB) and variable writing and paper speeds. Although these graphic level recorders can also be utilized for plotting spectra in conjunction with special frequency analyzers this is rarely done as XY-plotters are faster and more convenient to handle.

3.2.6 Equipment Selection

Selection of the appropriate data acquisition equipment depends on the test to be conducted and is largely determined by the number and location of the microphones with respect to the central measuring station. As outlined earlier, the simplest noise certification tests (from the view point of equipment and data analysis) are those required in ICAO ANNEX 16/Chapter 6 and Chapter 10, i.e. those relating to light propeller-driven aeroplanes. In both cases only one micropohone is needed, and - in principle (though probably never in actuality) - a simple visual reading from a precision sound level meter, set at A-weighting and detector speed "slow" would suffice.

A basic setup for a Chapter 3 (heavy propeller aeroplane and subsonic jet aircraft) or a Chapter 8 (helicopter) certification test would require between 3 and 8 microphones. In this case either a number of autonomous measurement stations (with one tape-recorder each) or a central multi-channel tape-recorder would be used. The system is calibrated by means of a pink-noise generator in addition to pistonphone calibration. Signals are then fed via individual preamplifiers to a multi-channel signal conditioner (amplification and filtering), followed by a multi-channel tape-recorder which is connected to a multi-channel after-recording monitor. The signal conditioner is conveniently connected to a gain-setting printer (where the individual gains of all amplifiers are printed out, since it is impractical to write these down by hand during the test).

One track on each tape-recorder must be used to record a time code, obtained from a master time-code generator. This helps to synchronize the flyover-noise time histories with the signals from the tracking system (such as a camera shutter impulse).

All such equipment would normally be installed in a control van or container, where it can be checked and calibrated prior to the actual test. It is cumbersome if the equipment is pretested in the laboratory, then dismantled and put together again at the test site, requiring a new calibration and check. In sophisticated noise certification test programs a well equipped control van or mobile measurement container should be used, since all the logistics for the non-acoustic equipment relating to tracking and atmospheric data acquisition must also be provided. (See Section 3.3 below).

3.3 Other Test Equipment

3.3.1 Aircraft Tracking Instrumentation

In the process of noise certification testing, the test-aircraft must be accurately tracked. Precise information on the trajectory in terms of flight path and flight speed is necessary for correcting measured noise data towards reference conditions. Three parameters, in particular, are affected by deviations of the actual flight trajectory from reference:

- o spherical attenuation (attenuation for geometric distance following the $1/r^2$-law),
- o atmospheric attenuation (humidity and temperature dependent sound absorption, expressed in terms of level-decrease per unit of distance), and
- o sound exposure time ("10-dB-down time").

Continuously tracking an aircraft is not necessary for a Chapter-6 or a Chapter-10 noise certification test. Here only the height above the microphone is of interest. In that case, determination of one point in the trajectory - preferably directly overhead the measuring microphone - suffices. But even for the relatively simple Chapter-6 test procedures it would still be more desirable to ascertain that the aircraft follows a level-flight path, not unintentionally climbing or descending. Determination of at least 2 points of the trajectory, e.g. one or two seconds before and after the microphone was overflown would be useful to obtain an indication of the actual flight path.

For all other noise certification procedures, where both centerline and sideline acoustic data must be measured and - more importantly still - where the noise level must be established in terms of an EPNL (i.e. Chapters 3, 5, and 8) tracking should be continuous - or at least a large number of positions in the trajectory must be measured.

Trajectory measurements are usually made with ground based equipment. Sometimes onboard systems (such as inertial platforms or aircraft mounted cameras) are better suited for the purpose. As far as ground based equipment is concerned some test ranges near airports have, sometimes extensive, permanently installed equipment. Most trajectory measurements are however made with mobile equipment since noise certification measurements are often executed at or near rather ill-equipped landing strips. Employment of mobile and ground based equipment generally requires good advance planning, especially, if time synchronization with onboard equipment and with several ground acoustic data stations is to be maintained.

Depending on the particular flight-test procedure and on the degree of accuracy required, one may select one of the following tracking methods:

Optical Tracking/Ground based Systems:

- single camera
- several cameras
- kinetheodolite
- laser

Optical Tracking/On-board Systems:

- forward/side-looking camera

Radio/Radar Tracking:

- radar
- microwave airplane positioning system (MAPS)
- radio altimeter
- Mini Ranger

An excellent survey on flight tracking methods is provided in |7, 8|.

The advantages and disadvantages of these various height-measuring and flight trajectory tracking methods will be discussed in the following.

(a) Optical Tracking / Ground-based Systems

Single camera

Aircraft height and lateral deviation from the vertical can be determined with only one camera. The optical axis of the camera must then be very accurately adjusted in the vertical. This is achieved by means of an inclinometer, laid directly on the camera-lens rim or by some appropriate bubble-level. Preferably the camera should be equipped with a Polaroid back-plate to allow immediate picture development in the field within a time span of about one minute.

Selection of the appropriate focal length of the camera lens depends on the (lateral) dimensions of the particular structural part of the aircraft to be used for distance determination (e.g. aeroplane wing-span or helicopter skids), on the typical height range and the preferred image size within the usable field of the picture frame. It would not be sensible to let the wing-span fill entirely the lateral extent of the frame (even though that would provide for the most accurate dimension-reading) but rather only between 15% and 30% at most. This would allow for some lateral trajectory deviations and would also permit the approaching aircraft to appear in the viewfinder in time for the operator to react and push the button. For a 35 mm slide camera, for example, certain focal lengths of lenses correspond to the following approximate fields of view:

150 mm ≙ 14 degrees, 300 mm ≙ 7 degrees, 600 mm ≙ 3.5 degrees.

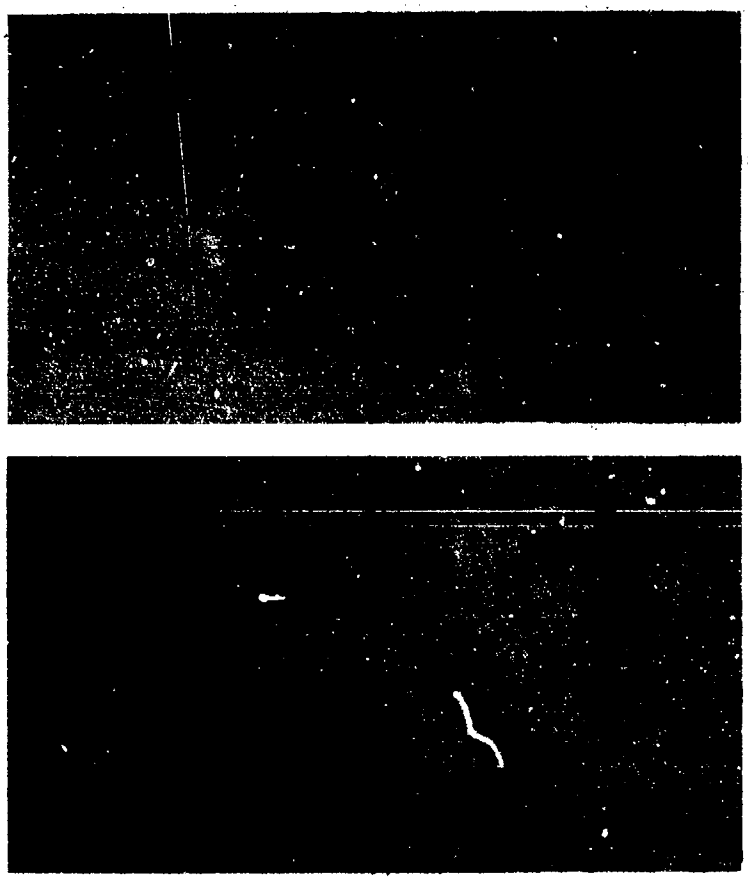


Fig. 3.22 Example of flight height and lateral deviation photographic check pertaining to "valid" and "invalid" test flight

The exposure time should be as short as feasable within the prevailing light conditions, since an aircraft overhead may fly an appreciable distance during the exposure time. An aircraft moving along its level trajectory at a speed of e.g. 75 m/s would fly 0.75 m during an exposure time of 1/100 s. That may be tolerable, since the blurring would occur in the longitudinal dimension, while the lateral dimensions used for the reading would not be much affected.

The camera with its lens in place can be calibrated in situ by photographing objects on the ground at appropriate distances. If that is not possible, the height H of the aircraft above the camera-lens can be calculated by means of the following equation:

$$H = f\ (S/S'),$$

where f is the lens focal length, S is the lateral dimension of the structural component selected for the purpose and S' is the dimension of the particular component as it appears on the film-negative.

A typical result for a propeller aeroplane in flyover (obtained in a Chapter-6 noise certification tests) is shown in Fig. 3.22 . Two cases are illustrated: one, where the aircraft was well within the reference flight-path and height, and another one, where it was too low and off to the side. The achievable accuracy by means of this method is not very high, but generally sufficient for noise certification purposes, where an error of several meters in 300 m would lead to only a fractional deciBel-error.

Several cameras

If a level flyover must be ascertained, at least two ground-stationary cameras should be used. Two cameras would also allow to determine the ground speed (provided the aircraft was not accelerating or decelerating, in which case three cameras positioned directly under the flight-trajectory would be a minimum requirement). The camera exposure click should be monitored on the same tape-recorder where the acoustic flyover event is recorded. Calibration of a possible time-delay between the shutter-operation and the actual taking of the picture may be necessary. In some cameras there is an appreciable delay between "pressing the button" and "taking the picture", in the order of perhaps 1/4 second. Within that time span, the aircraft may have already flown several tens of meters. When determining a ground speed, both the lateral and the longitudinal deviation of the aircraft at the time the picture was taken (and the exposure click recorded) must be accounted for. The principle of determining height and ground speed is illustrated in Fig. 3.23.

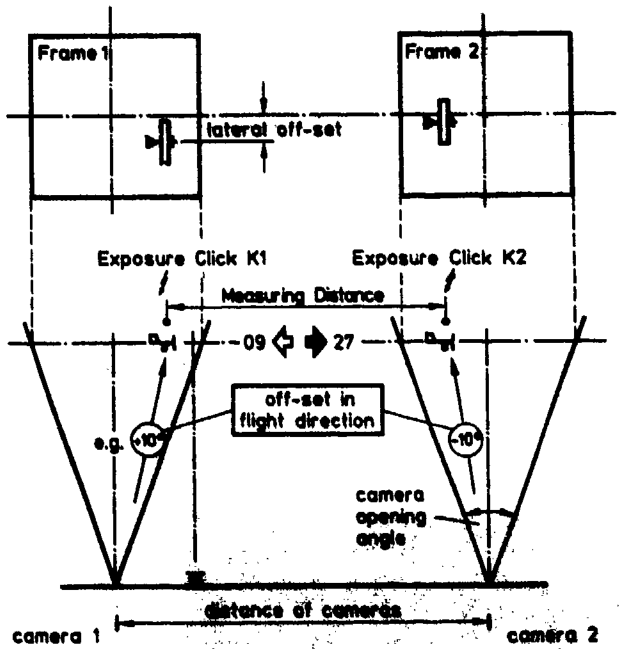


Fig. 3.23 Principle of height/lateral/longitudinal deviation and overground speed determination by means of 2 vertically orientated cameras

In cases where more accurate tracking is required, the number of cameras should be increased (up to e.g. 5). However, each camera station must be manned and if a number of autonomous acoustic measurement stations are also required, the test crew becomes substantial. In such cases it is preferable to employ more sophisticated tracking equipment, as discussed below.

Instead of accurately adjusting the cameras for verticality on a tripod, one may employ a "photo overhead positioning system (POP-system)". Such a system was utilized in a recent helicopter noise measurement campaign by the US-FAA |9|. Each of the several systems consists of two wires, parallel to the ground and in a vertical plane orthogonal to the flight path (Fig. 3.24). The photographer, lying beneath the POP initially positions the (hand-held!) camera to coincide with the vertical plane of the two guide-wires. He then tracks the approaching aircraft to trip the shutter at the instant when the aircraft crosses the superimposed wires. In this particular test a slide-film was used; by projecting the slides on a screen, a relatively high degree of accuracy in the order of 2% was achieved (considering the very simple and certainly elegant approach).

Kinetheodolites

Kinetheodolites (on sturdy support structures!) provide photographic pictures of the flight vehicle in rapid succession. The aircraft is visually followed through a high quality finder-scope. Azimuth and elevation of the optical axis of the theodolite - camera/telescope appears directly on the frame each time a picture is taken. Each film frame shows the displacement of the target from the optical axis. A picture may be automatically obtained at intervals of one or two seconds. The achievable

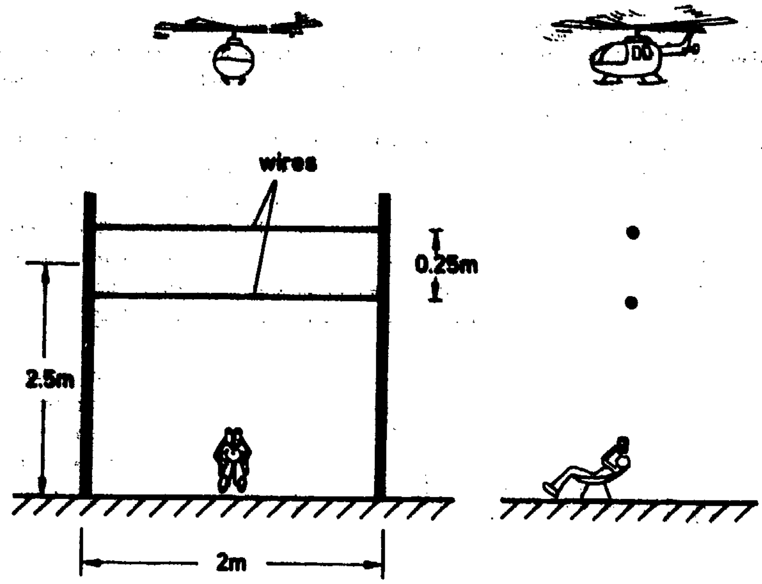


Fig. 3.24 Photo overhead positioning ("POP") system

accuracy across the line of sight of a typical Kinetheodolite (such as the ASKANIA Kinetheodolite 61 E, Fig. 3.25) for a typical aeroplane flyby at 500 m distance would be in the order of 0.3 meters. Such an accuracy is more than sufficient for the purpose. Along the line of sight, however, the accuracy is inherently more limited, especially, if the aeroplane is followed at some low slant angle, where the relative image size varies rapidly.

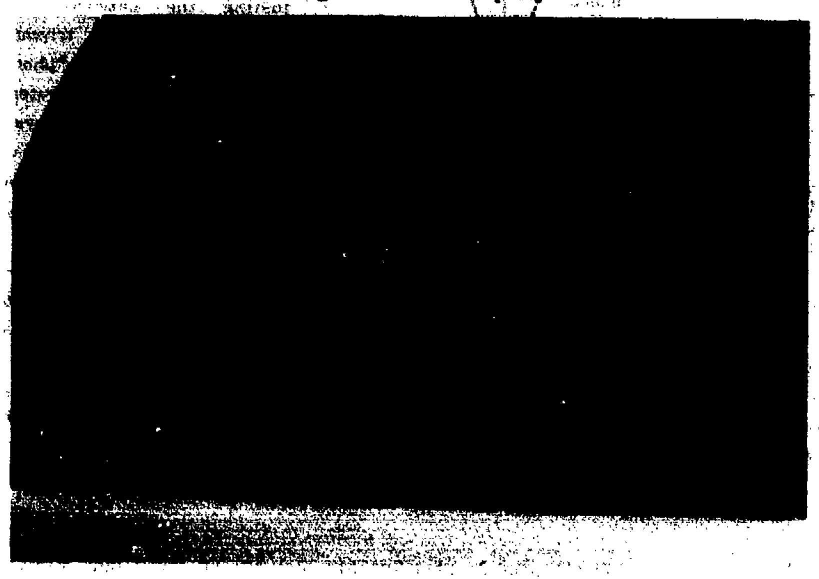


Fig. 3.25 ASCANIA Kinetheodolite 61 E

It is better therefore to employ two kinetheodolites, one on each side of the flight path (some 500 to 1000 m away from the track). Then the crossing of the two lines-of-sight allows very accurate tracking, within approximately 1 m absolute. Fig. 3.26 shows the geometries involved in a two-kinetheodolite trajectory measurement. It is clear that the kinetheodolite tracking data must be exactly synchronized with the acoustic events, i.e. both kinetheodolite time-codes must be recorded on the acoustic data tape.

Although it is often desirable to use more than one kinetheodolite (two, sometimes, though rarely, three) there are certain test procedures, where indeed just one kinetheodolite would suffice: Ideally, flight trajectories flown during noise certification tests, are "two-dimensional" (i.e. they lie within one vertical plane).

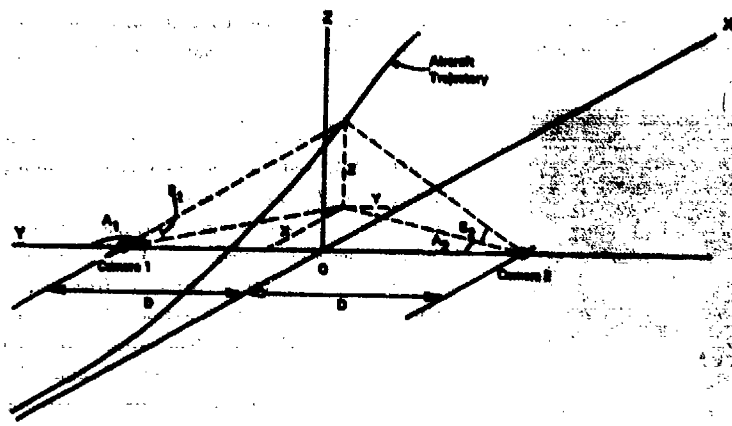


Fig. 3.26 Measurement geometry in flight tracking by means of 2 Kinetheodolites (from Ref. 7)

During a genuine take-off or landing approach flight test, for example, the aircraft follows the runway center line and only height information in a vertical plane through that centerline is of interest, assuming that the aircraft is always directly above the center line track. A single kinetheodolite, positioned near the middle of, and sufficiently far away from, the trajectory to be measured, would then keep the test aircraft in sight, without even moving the optical axis in the vertical, provided the range of elevation was small. There are special kinotheodolites that allow only a "left/right"-motion. For such systems the post-test processing effort naturally will be much less than if, say, two kinetheodolites with free movements about two axes were used.

Kinetheodolite-measurements are still considered to be the most reliable means for close range tracking of aircraft. Experienced operators are required, however, to follow the aircraft visually. Data processing is very laborious and time consuming, since all films have to be developed and manually measured frame by frame. Kinetheodolites are very useful for measuring trajectories where speed and acceleration of the aircraft must be determined. For noise measurements, where these are less important, single-picture cameras often suffice.

Fig. 3.27 DLR Laser transmitter/receiver

Laser Tracking Equipment

Optical rays in the infrared are used in laser-tracking equipment. Here, short duration bursts of laser energy from a laser transmitter (Fig. 3.27) are pointed towards the target which must be equipped with a retro-reflector (cat-eye-principle, Fig.3.28) to send the signal back towards a receiving telescope, whose output is directed to a 4-quadrant photo-detector. When the telescope axis is pointed precisely at the target, all quadrants receive an equal portion of the target-return-image, and the detector outputs are equal. An optical automatic gain control maintains constant average optical signal levels at the detector and any deviations are automatically adjusted in order to lock on the target image.

Fig. 3.38 Retro-reflector attached to underside of aircraft

To initiate tracking, the aircraft is first visually followed by a television camera attached to the laser transmitter; once the laser locks on the target's retro-reflector, tracking becomes automatic. Elevation and azimuth are determined directly from monitoring in two axes the position of the telescopes, while range is determined from the time-interval between transmitted and received optical pulse. Data must again be processed by a computer system, to provide the time-varying coordinates in tabulated or graphical form.

Lasers have only recently been introduced for aircraft tracking. Although the system is technically rather involved, it is very convenient to operate by one single engineer. It also provides on-line data processing, a tremendous advantage versus the KTH or the photographic camera-approach. It works for heights very close to the ground (within a few meters), in contrast to the radar-tracking system (see paragraph c below), where the conical radiation beam of the radar precludes measurements much below several tens of meters from the ground. Safety considerations must be observed, however, since some laser beams are hazardous to the eye, including the eye of the pilot towards whose aircraft the laser beam is directed!

The Societe Anonyme de Telecommunication has recently developed an Infrared Trajectography System, named the "MINILIR"-System. This system is capable of real time automatic tracking of a moving target fitted with an infrared source |10|.

(b) Optical Tracking / On-board Systems

Forward/downward looking Camera

Forward and downward looking camera systems installed in the aircraft are capable of achieving extremely high accuracies depending on the test conditions. Accurately surveyed ground targets are required, however. Of these, 3 or 4 must be visible in each film frame before the camera position (and thus the aircraft position) can be computed. Sophisticated calibration reading and corrective techniques are necessary, however, to obtain accurate data. Weather and ambient lighting often hinder testing. Data processing and analysis are slow and waiting time is costly, particularly if data turns out to be unsatisfactory.

For a "Chapter-3" approach noise certification test the Fokker Company has successfully employed an 'Automated Landing Flight Path Measuring System', termed "ALAND". Here, position and velocity data during automated approach/landing trials are obtained. This subsystem has been primarily used to check the performance of the Fokker 100 aircraft automated landing system. The function as such is performed by a combination of photogrammetry and inertial sensing: A nose-mounted camera takes approximately 6 pictures per second of the runway (lights) during the last phase of the approach and landing. The output of the flight 'inertial navigation system' (INS), of a radio altimeter and of a pressure altimeter encoder are recorded in the digital instrumentation recorder |11|.

After a flight, the film is developed and of each landing approximately 5 pictures are used to establish the exact location and attitude of the aircraft. These data together with altitude information from the radio altimeter and the pressure-altitude encoder is used to update the flight INS. It turned out that the flight path coordinates were established with an accuracy of 10 m at 2 km before the runway threshold, reducing to 0.6 m in x- and 0.3 m in y- and z-coordinates during touch down and roll out.

(c) Radio and Tracking Radar

Radar Tracking using Transponders

Ground-based radars usually provide somewhat less accuracy than kinetheodolites, but their operation and data processing is fully automated. A transmitting/receiving antenna as used by DLR |12| is shown in Fig. 3.29. The electromagnetic pulse emitted by the radar transmitter is reflected directly from the aircraft back to the receiving antenna. Sometimes a special transponder on the test-aircraft is used to reflect the appropriately amplified signal (probably at a different but known frequency) back to the ground station. The primary radar systems in an FAA test used a 9.1 gigaHertz-signal. Systems are available up to 30 gHz (≙ 1 cm wavelength). In operation the system measures the time between pulse emission and reflected signal return with an accuracy in the order of several nano-seconds; this translates into a slant distance uncertainty of approximately 1 m. It should be understood that the re-transmitted frequency towards the ground station will have undergone a Doppler-shift on account of the motion of the object to be followed.

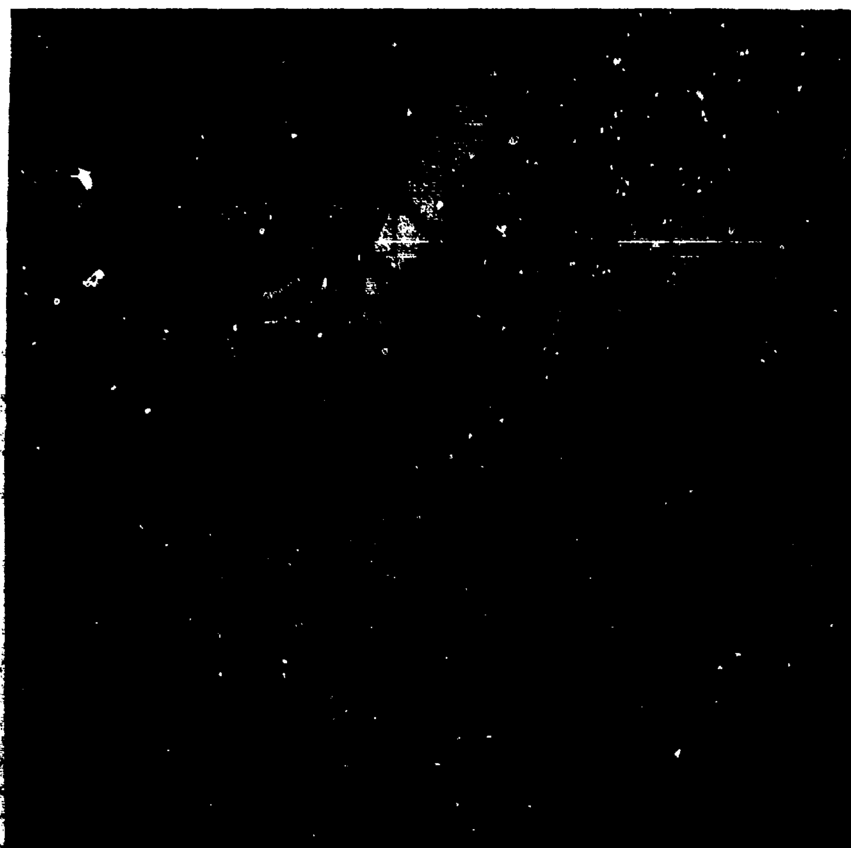


Fig. 3.29 Radar tracking transmitting/receiving antenna (DLR)

In practice, once the operator has directed the antenna system and the range servo system inside the "target acquisition window", the radar can switch into an automated tracking mode. It then determines the motion of the target-aircraft in terms of range, elevation and azimuth. Data are converted to Cartesian coordinates by means of a computer system in order to yield the required position-information in form of tabulated or plotted data. Only one tracking radar is necessary, since it measures all 3 coordinates of a target simultaneously, a distinct advantage vs the use of a KTH.

<u>Microwave Airplane Positioning System (MAPS)</u>

The Boeing Commercial Airplane Company recently introduced their "Microwave Airplane Positioning System (MAPS)" for noise certification testing of 757 and 767 subsonic jet aeroplanes |13, 14|. The system (<u>Fig. 3.30</u>) measures range and range rate from several ground transponders to an airplane and computes the airplane position using a KALMAN filter algorithm (essentially a "least square error"- algorithm). The airplane position relative to a fixed earth coordinate system is available for recording and for cockpit display several times per second.

In the Boeing approach, a number of microwave transmitter/receiver (T/R) units are located at surveyed coordinates in a respectively optimum ground pattern. Airborne equipment includes an "interrogator", a digital processor, data storage units, pilot guidance indicators and a quick-look engineering station. In operation the airborne system interrogates each ground T/R-unit in serial fashion and computes slant range and range rate from the response. The computer performs position calculations in real time. Data are used to drive panel instruments which allow the pilot to follow a specific flight profile.

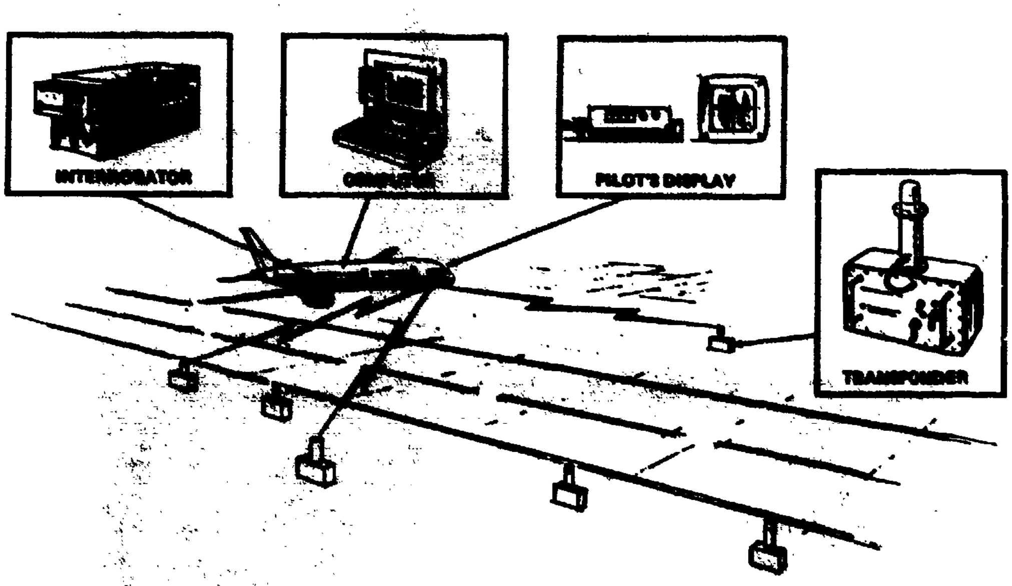


Fig. 3.30 Transponder Layout for Microwave Airplane Positioning System (from Ref. 13)

The flight [illegible] (aircraft positioning) system as used by the Fokker Company in certificating the [illegible] is quite similar to the Boeing MAPS. The system was developed in 1977 based [illegible] Mk III system (MR Mk III) and an On Board Processor (OBP) for real ti[illegible] the aircraft using standard cockpit instruments. The system has also been used during exterior noise measurements (see Ref. 11). The MR Mk III is a pulsed radar distance measuring system, operating at a frequency of 5.5 GHz. The MR Mk III console (situated in the aircraft) interrogates 4 groundbased transponders. They are placed at locations with known coordinates. To envisage the movements of the aircraft (pitch and roll) two transponders are located longitudinal and the other two lateral on opposite sides of the runway. The flight path lies within a quadrangle defined by the transponders. For calculating the position of the aircraft one laterally and one longitudinally located transponder is used. In this way the position error is made as small as possible.

The aircraft speed and height are determined by measuring aircraft static pressure, impact pressure and total air temperature. The onboard processor controls system-timing, performs data acquisition and calibration, calculation, data conversion and data output. Calibration data is put into the processors non-volatile memory before a measurement session. A special ARINC transmitter drives the localiser- and glide-slope-bars through a dummy NAV receiver, using signals generated by the OBP. Thus the pilot is provided with guidance information which enables him to fly a predefined flight path.

Comparison with the more traditional KTH procedure shows these two systems' accuracies as better than 2 meters, provided they operate within their design envelopes. This precludes measurement of aircraft altitudes less than approximately 50 m, essentially eliminating take off and landing approach measurements. In that case other means of altitude determination are necessary such as radio altimeters or pressure altimeters which have their own limitations.

(d) Tracking System Considerations

For purposes of noise certification (in contrast to airworthiness type certification testing) tracking requirements call for an accuracy of not much more than 1%, since errors of that magnitude would still only result in fractional deciBel-errors. Hence, the inherent measuring accuracy of (albeit well maintained and operated) kinetheodolites, laser or radar tracking equipment in the order of 0.1 to 0.3 m at measuring distances is about one order of magnitude too good, leaving some comfortable margin towards less than ideal operation.

If test cost and availability of sophisticated tracking equipment at the test site is of concern, one or several vertically orientated cameras will suffice for most noise certification tests. However the cost of in-the-field operation and set-up (one man per camera) and of the subsequent laborious data-processing must be weighed against the other aspects of using more sophisticated and automated tracking methods, such as kinetheodolites, lasers or radar. Laser tracking is probably the most accurate and versatile tracking method presently available; unfortunately, it is also quite expensive.

3.3.2 Meteorological Instrumentation

Precise information on the prevailing atmospheric conditions at and near the test site, at and near the test-aircraft, and in the air space between the test-aircraft and the measurement station (i.e. along the sound-propagation path from the source to the receiver) is important for correcting measured acoustic data to reference conditions. The most important parameters are temperature and humidity, and wind-speed and -direction; ambient pressure is usually of less importance.

As had been stated earlier, ambient temperature at the test aircraft affects all speed-related parameters because it changes the sound speed; it follows that the same flight speed and rotational speed (of propellers and helicopter-rotors) corresponds to a different local Mach-number. The combination of temperature and humidity along the sound transmission path affects the atmospheric absorption (attenuation). Also, a temperature gradient between aircraft and microphone may bend a sound-ray, making source identification and path-length definition difficult.

Winds aloft, along the sound transmission path and at the ground test-site, affect the flight trajectory of the test-aircraft, the propagation-path of the radiated sound from the test-aircraft to the microphone, and may generate excessive "wind-induced" noise at the microphone.

Atmospheric turbulence (localised variations in wind-velocity and temperature) may cause a scattering of sound waves during propagation.

Ambient pressure affects the indicated airspeed, has also some effect on the aircraft-engine performance and will slightly change the signal-strength of pistonphone calibrators.

For these reasons ANNEX 16 either specifies atmospheric "no-correction test-windows", or - if measurements must be made outside those windows - prescribes correction procedures to eliminate atmospheric effects from the test-data. Hence, all of the above atmospheric parameters must be known and monitored during the test.

(a) <u>Ground-based Equipment</u>

<u>Test-site Meteorological Station</u>

The measurement of temperature and humidity near the test site will require the sensing elements 2 m or 10 m (depending on the particular ANNEX Chapter) above the ground, mounted on a suitable support-structure. There are numerous commercially available temperature/relative-humidity sensors, such as the VAISÅLÅ HMP14 probe, which employs a thin-film capacitive sensor for relative humidity and a linear thermistor-resistor for temperature measurement. Another useful instrument is the LAMBRECHT type 819 psychrometer. These sensors have a (really not necessary) fast response time of fractions of seconds. They measure temperature typically within +/-0.2 °C, and relative humidity within +/- 3%. Ambient air-pressure can be measured by one of many commercially available absolute pressure indicators or transducers, such as the LAMBRECHT meteorograph type [illegible]. When measuring such relatively slowly changing parameters one reading or data-point every 5 to 10 minutes suffices.

Measuring devices for local wind-speed and -direction (such as the LAMBRECHT type 1465 G) typically comprise a 3-cup anemometer for wind speed in combination with a wind-vane, which is attached to a potentiometer to indicate wind-direction. The anemometer only measures the horizontal wind component (≙ parallel to ground). Its output is separated into a head- or tail-wind component and a cross-wind component, both of which are specified in the appropriate ANNEX-Chapter/Appendix. Wind information must be measured with a fast-response detector to "catch" short duration gusts, but the "30-second"-averages are also required for the corrections. A typical anemometer would determine wind speed with an accuracy of 2% (or about +/- 0.1 knot in a 10-knot wind) and wind direction to within approximately +/- 2 degrees.

<u>Sodar</u>

Although Sodar has been developed for wind-shear detection around airports, it can be used to determine atmospheric and wind information between the ground station and the test aircraft in the context of noise certification. Using such a system is much more complex than using a simple ground based anemometer, since computer-processing is necessary to provide the three-dimensional wind information along the line of measurement. A Sodar is capable of measuring wind speed and direction by emitting acoustical pulses into the atmosphere and measuring the intensity of the returning pulse echos. Changes in wind speed and direction will cause measurable changes in intensity and shifts in frequency due to the occurrence of a Doppler-shift. With a three-antenna-system Sodar, wind speed in three dimensions (and thermal atmospheric structures) at various altitudes in the atmosphere above the test site can be determined. The height at which these values are measured is determined by the elapsed time of the returning echo after emission of the initial pulse. Thus layered information at, say, every 20 m in altitude towards, and even above and beyond, the test-aircraft can be obtained. The accuracy of the REMTECH Doppler-Sodar, for example, is specified to be within 0.3 m/s for wind speed and within 3 degrees for wind direction.

In most cases Sodar-information will not be directly used to correct acoustic data for wind-effects. Sodar is often used to establish whether excessive wind or substantial macroscopic turbulence exists between the test aircraft and the measurement station that would not be apparent from the ground-data.

Airport Tower

The required meteorological information can often be obtained from a nearby airport tower, if the test-site is close to an airport (which "closeness" in itself entails however some rather severe disadvantages!). An airport tower continuously monitors macroscopic atmospheric conditions in the course of its normal operation and will usually have information available on wind speed, wind-direction and temperature near the ground and at altitude. It is often better, though, to obtain measurements at the test site.

(b) Airborne Equipment

Sounding Balloon

Weather balloons can be used to determine changing wind directions above a test site. They must be (3-dimensionally!) tracked by means of an extra KTH, while the accuracy of the information - as far as wind is concerned - is still rather limited, quite apart from the excessive cost of operating balloons for purposes of noise certification atmospheric sounding. Such a free-rising meteorological balloon (also called piloted balloon or "pibal") would initially have a diameter of about 30 cm; it would then rise to an altitude of 5000 to 7000 m, where it would burst at a diameter of approximately 60 cm.

A pibal should be released approximately once per test hour and be tracked to a height greater than the maximum expected height of the test aircraft within the next hour.

Fig. 3.31 Launching of tethered radio sonde for meteorological sounding (used by NASA Langley at Wallops Flight Center)

Tethered Radio-sonde

A tethered radio-sonde can provide information on temperature, air-pressure and humidity, as well as on wind-speed and direction (Fig. 3.31). Temperatures are sensed by a thermistor. A thermistor is a device that changes electrical resistance in proportion to the air temperature; the variation of resistance is however not linear and individual calibration is required. For wind, a cup-anemometer and a combination of a magnetic compass and a potentiometer for wind direction is used. If the air is turbulent, the balloon may oscillate laterally and thus produce apparent fluctuations in the measured average wind speed. Also, the axis of the cup-anemometer may be tilted from true vertical. Such potential errors should be assessed by periodically halting the balloon during ascent and descent.

Data from the radiosonde should be transmitted continuously by a UHF-transmitter to a receiver in the ground station. Data should also be plotted on a printer showing time of day, static air pressure (or the difference between the pressure at ground and aloft, which is a measure of the height above ground level). Dry and wet bulb temperature and speed and direction of the horizontal component of the wind should be printed out.

The tethered radio-sonde should be let up and hauled down, if feasible, at least once per hour. An ascent rate of 30 to 60 m/minute should be achievable. The tether-line should be about 1000 m long. Because letting up and hauling down the tethered radio-sonde is noiseless and far away from any flight path flown by the test aircraft, it should be possible to operate the radio-sonde while the aircraft is being tested. The variation of pressure with height is determined as the difference between pressure at the surface and the pressure aloft.

Meteorological Airplane

Another common and cost-effective way to obtain vertical atmospheric information is the use of an atmospheric probing aircraft (Fig. 3.32). The aircraft should fly along ascending and descending paths parallel to the microphone arrays. Alternatively, a curved ("cork screw type") path around the center microphone can be flown. Meteorological data should be sampled every 30 m in height. The aeroplane should climb to an altitude that exceeds the top altitude of the test plane by at least 100 m. Typically, the aircraft would conduct a probing flight twice per hour. The rate of descent or climb should be low enough to accommodate the response time of the instrument for the gradients in temperature and humidity. The total time to complete an ascent/descent manoeuvre should not exceed 10 to 15 minutes. To avoid interference, the meteorological flights should not begin until the test aircraft has departed from the test area. The test aircraft may hold somewhere while the meteorological data are sampled.

The height as calculated from an aircraft static pressure measurement will be accurate to within +/-3 to +/-5 m for heights greater than approximately 30 m. Below that, ground effects are known to degrade the accuracy of a pitot-static system. In that case a radio altimeter is recommended.

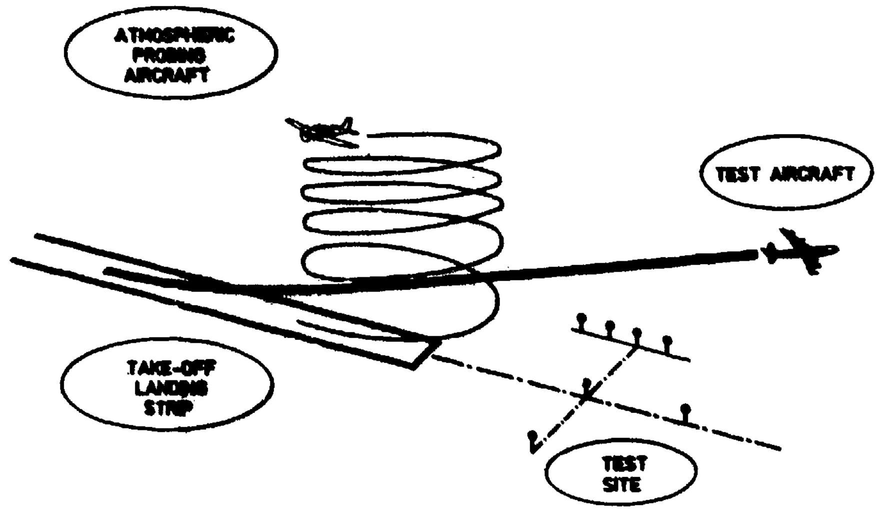


Fig. 3.32 Schematic of monitoring atmospheric parameters above test site by means of a probing aircraft

3.3.3 Time Synchronisation Equipment

In order to correct for deviations of the actual flight path from a reference flight path (specifically for atmospheric attenuation) the exact distance of the aircraft at the time, when the signal for 'maximum tone-corrected Perceived Noise Level' (PNLTM) was emitted, must be known. In addition, the flight-operational and engine parameters at that same "instant" in time should be available.

Therefore, time-synchronization between acoustic and flight-trajectory recordings is very important. Every optical flight-tracking station (camera or kinetheodolite) must transmit (preferably by radio-signal) a synchronization pulse each time a photograph is taken. In the case of a kinetheodolite (KTH) such radio-signals would be related to the shutter trip. A typical frequency value for a helicopter flyover KTH-sequence is, for example, 0.5 Hz. These synchronization pulses are recorded on the cue-track of the data-tape-recorder. At the master station receipt of each synchronization pulse could then be used to obtain a print-out of the exact synchronization instant (with better than a 1 millisecond resolution).

While this procedure synchronizes flight-path and emitted sound signature, the aircraft-operational parameters, such as rotor or propeller RPM, indicated air speed, torque, or any other pertinent engine-parameter must also be recorded. As an illustration, a procedure that was employed by a British team |15| for helicopter test flights will be briefly described. In this case, the cock-pit instrument panel was continuously photographed at a rate of one photo per second using a 16 mm movie-film-camera. Film casettes, containing several thousands of frames were used, which allowed casette-changes in day-light. Each test flyover was identified by a number written on a note-pad attached to the cockpit-panel (Fig. 3.33). Synchronization of the noise recordings (on the ground) with (a) a ground based tracking camera and (b) the movie-camera on board was achieved as follows: each time a ground camera was operated, it fired a 27 MHz radio-signal. The signal was received through the helicopter's on-board 27-MHz-receiver, which - by means of a special camera control unit - caused high-intensity LEDs to light up. These LEDs were mounted in an analog clock on the cockpit and visible to the movie-camera. In the case described synchronization to within 1 second was achieved, where the '1-second' is a consequence of the selected movie-camera photograph-sequence.

Such a comparatively long "uncertainty-time" is no problem, since operational parameters of the aircraft do not change appreciably within one second. This rather lax tolerance must not be confused with the much more stringent requirements for flight tracking, where the position must be known to within a fraction of a second, since the aircraft may fly several tens of meters during such a time-span. This approach involved however visual inspection of each test-run movie to identify the instants, when a ground camera was operated.

Fig. 3.33 Camera recorded cockpit instrumentation panel at time-instant when ground based camera trigger pulse was released

Alternatively, time synchronisation between continuously operating tracking devices and the readings of on-board parameters can be achieved by means of filming the display of a digital clock on the instrument-panel. In that case the clock itself must have been calibrated to a very accurate ground-located master clock, monitored in turn on the data-tape by means of a time-code recording.

If recorders onboard are used then a start/stop detector (SSD) - as used by the Fokker Company - is helpful. Its main function is to start and stop the recorders in the aircraft simultaneously with ground based recorders and to advance the ID-code of the time code generator. The commands from the central ground based station are received in the aircraft by a VHF-FM receiver and detected by the SSD. The receiver is part of the SSD. The SSD also provides a start and stop criterion for the flight path measuring system.

3.3.4 On-board Aircraft Instrumentation

While ANNEX 16 specifies that certain aircraft flight parameters must be determined by aircraft-independent means, such as flight height and ground speed, and - if necessary - aircraft side-slip direction (in the presence of strong cross winds), certain other parameters must be measured on-board, notably indicated airspeed, aircraft attitude, onflow direction and speed ("wind vector"), outside temperature and ambient pressure. To determine the helical blade tip Mach number of a propeller or the advancing blade tip Mach number of a helicopter rotor, the blade-tip or rotor-tip rotational speed, the true flight speed, and the true ambient (static) temperature must be precisely known.

All engine related operational parameters are recorded on-board the aircraft. Relative humidity may also be determined by on-board means. By comparing outside air temperature and relative humidity aloft with those obtained near the ground one may obtain an indication of the general temperature/humidity pattern between the aircraft and the ground measurement station.

(a) Propeller or Rotor Rotational Speed

Usually, there is a propeller or rotor tachometer on the instrument panel, calibrated in terms of revolutions per minute (RPM). These kinds of instruments are not accurate enough to provide the rotational speed to within the necessary +/-0.1%; such an accuracy is required to ultimately obtain the blade tip Mach number to within the third decimal. Especially if the temperature or Mach number correction factor is to be determined by means of varying the rotational speed (see Section 2.5.7) the rotational speed must be measured by a more accurate procedure.

One such method is to employ "resonant reed tachometers" (Fig. 3.34); these are attached to a suitable point on the aircraft-structure and resonate in response to the vibratory environment in the aircraft. This resonance is directly related to any, however slight, rotational imbalance of the rotating system. One can then, in a straight-forward manner, read the propeller rotational speed from the beam-resonance frequency.

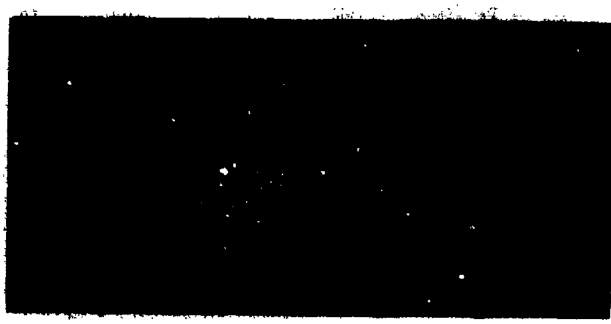


Fig. 3.34 Resonant Reed Tachometer (FRAHM)

This type of instrument might still not be accurate enough. Light-beam emitting devices directed towards the propeller blade which carries a small reflecting pad are also used. Electronical counting of the reflected pulses provides a direct indication of the propeller rotational speed.

A third possibility is to monitor the acoustic signature inside the cockpit. The rotation of the propeller or the rotor expresses itself through an acoustic line-spectrum consisting of a blade-rotation fundamental and a number of harmonics. Selecting any particularly strong harmonic within this line-spectrum will yield the rotational speed with a very high degree of accuracy.

In a helicopter, the main and the tail rotor are mechanically coupled with a known gear ratio; any particular and suitably strong tonal component in the cabin interior narrow-band acoustic spectrum may then be taken to derive rotational speeds. Since the frame of reference is the aircraft, no speed-related Doppler frequency shift occurs. Further information on engine-rotational speed measurement may be found in |16|.

(b) Air Speed and "Wind Vector"

The flight speed of the aircraft is normally obtained on the basis of a Pitot-static read-out on the cockpit instrument panel. Speed is initially available in terms of the "indicated airspeed (IAS)". The value of the IAS, however, still contains instrument errors and errors resulting from the installation of the sensor close to aircraft structural components; the latter ones are termed "position errors". The actual amount of these errors is available from the aircraft-specific flight manual. IAS is also affected, among other things, by aircraft weight and the particular configuration as flown, notably by the wing-flap angles. These effects may quantitatively be determined from information in the flight manual. Accounting for these errors will now provide the "calibrated airspeed (CAS)". The CAS must further be converted into the "true airspeed (TAS)" by considering deviations from ISA sea-level atmospheric conditions of ambient pressure (flight height dependent) and temperature utilising appropriate tables. Since flight Mach-numbers in noise certification procedures never really exceed a value of approximately 0.35 any compressibility effects on the pitot/static-reading can be neglected.

Most modern aircraft are equipped with an on-board air-data-computer which provides TAS directly from IAS-information.

Both aircraft attitude and wind vector are of interest in the context of noise certification. Since aircraft-specific noise generators, most notably propellers and rotors, exhibit a pronounced directivity, it can be important to know their flight-attitude with respect to a geodetic coordinate system. Furthermore, the noise generation process as such of propellers and rotors is also affected by the air onflow direction and velocity (i.e. by the "wind vector"). Aircraft attitude can be determined by an on-board gyro or inertial navigation system. The wind vector can be derived from information on aircraft angle-of-attack ("alpha"), aircraft angle-of-side-slip ("beta") and TAS. In the practice of noise certification one can assume that a flight condition involving a relative side slip does not really occur. Therefore, the wind vector can be readily derived from speed and angle-of-attack information only. More directly, true airspeed and wind vector, respectively, can be determined with the (DORNIER-developed) "Flight-Log" (Fig. 3.35). It uses a light and fast-

Fig. 3.35 Dornier-developed "Flight Log": an airborne true flight speed and aircraft angle-of-attack/side-slip indicator

responding rotating "windmill-wheel" which is attached to a cardanically supported "wind-vane". The rotational speed of the "windmill-wheel" and the vane-direction are electronically monitored to provide a direct and very accurate measure of flight speed and wind onflow direction. Understandibly, this instrument must be placed at the tip of a sufficiently long nose boom on the aircraft and outside of any aircraft-related flow-disturbances.

(c) Ambient Temperature and Relative Humidity

Outside air-temperature can be measured by a number of commercially available thermometers such as those manufactured by the Rosemount Company. Modern sensors for measuring outside air temperature in the aircraft are always total-temperature probes. They typically use a tube-shaped housing (Fig. 3.36) mounted parallel to the free-flowing air outside of the boundary layer of the fuselage. Internally there is some sort of a temperature- sensitive resistance element. On account of

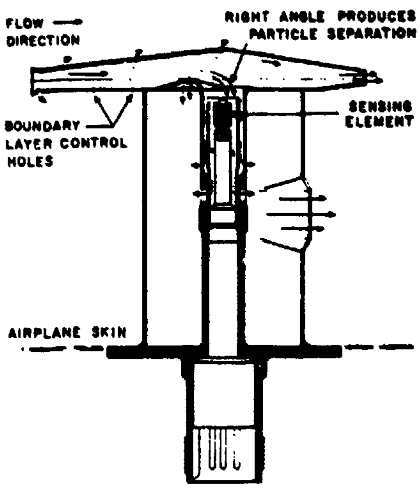


Fig. 3.36 Internal structure and housing for airborne temperature or humidity sensor (Rosemount)

internal air-flow deflection ahead of this element the air is turned by 90° (in the case shown) before it passes through the measuring element. Thus water and dust particles leave the probe without affecting the element itself. The air which enters through the tube orifice is nearly totally decelerated and adiabatically compressed. The element thus essentially measures static temperature. At the typical flight speeds in noise certification the temperature rise on account of compression can be safely neglected. Such "resistance thermometer" have a typical measurement range from -200 °C to +300 °C, more than sufficient, of course, for noise certification purposes; this type of thermometer is also very accurate and widely used. An excellent survey on temperature measuring devices for use on aircraft may be found in |17|. Outside relative humidity can be determined with instruments utilising the humidity-dependent capacity

Fig. 3.37 Humidity sensor elements (Vaisälä)

change of a dielectric condenser. Such an instrument would be for example the "Humicap" manufactured by the VAISÄLÄ-Company. A photo of humidity sensor elements appears in Fig. 3.37. An element of this kind could be mounted in the same housing as shown in Fig. 3.36; the device would then represent an airborne humidity measuring unit. Details on humidity measuring techniques from atmospheric probing aircraft can be found in [18].

3.4 Test-Site Selection and Set-up

3.4.1 Criteria for Site-Selection

Selecting an appropriate test site is probably one of the most crucial decisions that must be made by the engineer responsible for planning a noise certification test program. A number of important criteria must be checked: If actual take-offs and landings are required near the acoustic measurement stations, then the test site must be close to an airport. If, however, that airport is very busy, it will be next to impossible to run a smooth test program. Under normal circumstances the airport traffic has preference above the test flights. Hence, commercial airports are not suitable for certification noise testing.

Busy air traffic near the test site not only constitutes a flight hazard but also produces disturbing noise which might invalidate the test results. DLR frequently uses the Braunschweig airport (EDVE) for noise certification testing, a small municipal type airport with no commercial traffic. Only GA-type aeroplanes use this airport. Even so, it is difficult to find "quiet" periods to conduct a test flight (which itself may take no longer than a few minutes of active data taking).

A smaller - preferably abandoned - airport or landing strip has distinct advantages. The runway provides a visual cue to the test pilot for finding and passing overhead the central acoustic measurement station, provided the flight trajectory is parallel to, and to the side of a runway. In this case an experienced pilot can readily fly alongside unless the cross-wind component is too strong.

If the airport was not in active use, air-traffic related noise should be minimal, a decisive advantage. An abandoned airstrip, however, would not normally have an air-traffic control tower, which could provide local weather information. Since meteorological data should be obtained by the test crew anyway, this is probably not a severe handicap.

Although a concrete runway is necessary for jet-aeroplanes or heavy propeller-aeroplanes to take off and land, the actual measurement site should be away from a concrete surface. ANNEX 16 calls for an extended area with short cut grass, above which the microphones should be positioned at a height of approximately 1.2 m and where no nearby reflecting surfaces (e.g. buildings, trees) would interfere. Hence, though the general orientation of the test-flight trajectory would be close (i.e. parallel) to the runway, the test site itself would be off to the side and in a suitable grass-covered area.

It is somewhat ironic that ANNEX-16/Chapter-10 now requires an artificial round hard surface very close to a grass-surface below the inverted microphone (see Fig. 2.22). It would seem more straight-forward to take advantage of an existing hard concrete surface close to the beginning or to the end of a runway, or of a nearby taxiway. In such cases the microphones could be positioned directly on the surface or could even be inserted in a hole into the concrete (Fig. 3.38) to provide ideal non-reflecting conditions. Thermal turbulence directly above a concrete surface might however occur during periods of intense sun-shine. Associated problems could be reduced by applying a layer of white paint around a sufficiently large area surrounding the microphone.

Fig. 3.38 1-inch-diameter condenser microphone embedded in concrete runway surface

If the presence of emergency landing facility or runway visual orientation for the pilot is of less concern, testing can be conducted away from runways. In certification testing there occurs hardly ever an actual take-off or landing. Rather, reference flight trajectories are intercepted and subsequently followed for noise testing. In these cases (subsonic jet, heavy propeller aeroplane and helicopter noise certification testing) it might be better to use a remote test site somewhere "out in the country" and away from any airport-related air-traffic. Finding a suitable site in a densely populated area, as in Central Europe, may however be difficult.

The availability of electricity close to the test site is usually a minor concern. Most of the equipment can work from batteries. If excessive amounts of electricity would be required (say several hundred Watts), as for driving 'visual approach slope indicators' or a number of tape-recorders and analysers, a small power generator may be necessary.

The elevation of the test site above mean sea level affects the acoustic power produced by the aircraft engines. The influence of reduced atmospheric pressure is negligible at elevations from zero to 300 m, light effects must be expected up to 1000 m, and above that elevation increasingly larger adjustments to the measured sound pressure level are required, if the reference elevation is sea level.

3.4.2 Test Set-up

(a) Surveying

In order to accurately position the microphones and the tracking equipment with respect to the flight trajectory, the prospective test site must be accurately surveyed. The procedures will be illustrated for a representative test site at some airfield (Fig. 3.39) in the United Kingdom, where DLR, WHL and CAA jointly conducted a helicopter noise test |19|. This particular test went beyond the scope of a Chapter-8 noise certification.

This particular test aerodrome has 3 run-ways, 03/21, 12/30, and 07/25. Here 0° (≙ 00) corresponds to North, 90° (≙ 09) to East, 180° (≙ 18) to South, and 270° (≙ 27) to West. This airfield thus provided 3 options for a measurement set-up. All three options were surveyed prior to the test. Thus a quick re-arrangement of the instrumentation set-up was possible, should the prevailing long-term (like one day) wind-direction change from within, say, 15° to both sides of a runway to 15° of another runway. In the particular helicopter noise test, 3 microphones had to be positioned orthogonally to the flight track. There was one center microphone, and one each 150 m to the left and the right side of the center microphone. The test involved all three procedures (take-off, horizontal flyover, and landing approach) and all flight trajectories had to be measured very accurately. This was done - in this case - by means of 5 cameras positioned along the flight track: two cameras before, two behind of the center microphone and one camera close to the center microphone.

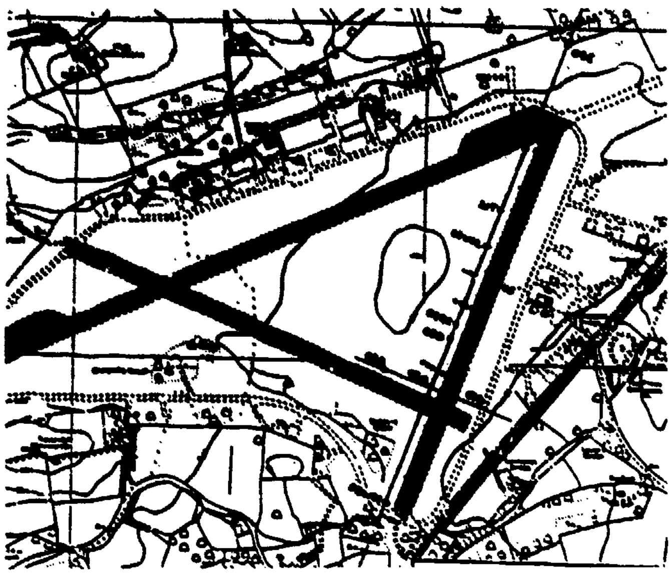


Fig. 3.39 Airfield in the UK with 3 runways used as flight noise measurement test site

The basic test set-up (as sketched in Fig. 3.40) consisted of the 3 lateral microphones and the 5 cameras. Their locations had to be predetermined at appropriate positions besides each of the 3 run-ways that were to serve as pilot cues. In addition, there were two other markings: the rotation point for the take-off test and the location for the precision approach path indicator ("PAPI"). All these points (3 microphones, 5 cameras, rotation point, and PAPI locations) had to have fixed positions with respect to each other. Peripheral equipment, such as the control-van and the weather station in particular, were positioned at a convenient location "out of the way".

Following the edge of the runway chosen as a datum line, microphone and camera locations were carefully marked, using a surveyers tape. Small inaccuracies (in the order of one or two meters) in the microphone-positioning can be tolerated. Any inaccuracy in the positioning of the cameras

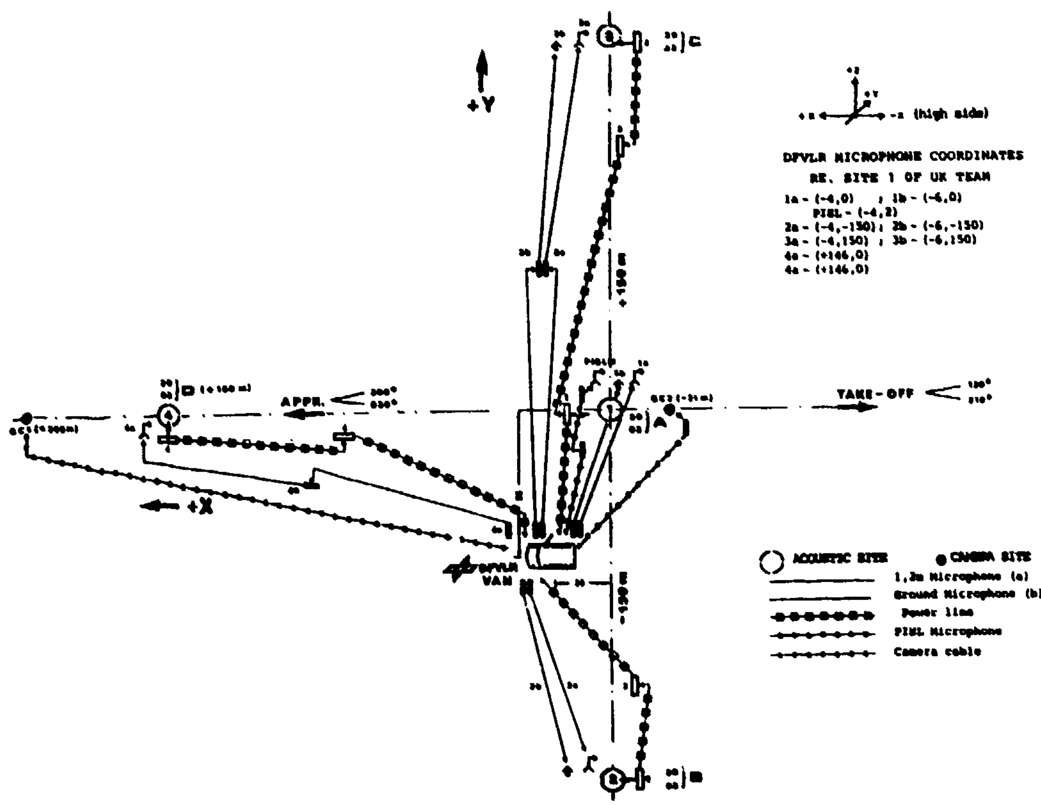


Fig. 3.40 Typical set-up and cabling map for aircraft noise test

would however have rather adverse consequences, as their relative distances directly enter into the ground-speed. To accurately align the array of cameras (and to some extent also the array of microphones) a surveyor-type theodolite is indispensable. This theodolite can also be used to determine any undulation in the test site surface. A hardly noticeable height variation of one or two meters in the area of the cameras would influence the effective aircraft flight height above ground. The microphones were positioned away from any reflecting surfaces (including the control van). Generally, there should be a distance of at least 10 m between the concrete runway edge and the closest microphone, since the change in ground impedance from concrete to grass affects the sound signature under grazing incidence conditions. Also, relative positioning accuracies in the horizontal plane, between microphones about 150 m apart, should be better than +/- 1 m.

Once the primary, as well as the alternate, locations of the center microphone station and of the lateral microphone stations were established, the flight track and the significant points on the track, such as the rotation point, were marked. For this purpose a number of fairly large, prominently coloured (orange) blankets were used along the track, every 100 m, or so, plainly visible to the pilot for orientation.

Of course, similar considerations apply to other than Chapter-8 type test. For example, in noise certification testing of heavy propeller aeroplanes or subsonic jet-aeroplanes (Chapter 3), the lateral microphone array must be 450 m to the side, with at least one, preferably several, check microphone(s) on the other side of the track, again at 450 m distance. Their positions would have to be accurately surveyed. Likewise, the position relative to the flight track of KTH-, radar-, or laser-equipment, if of the mobile type, or of ground-based transponders for the MAPS set-up, would have to be accurately determined.

Such surveys and location markings should be done well in advance of the actual testing. All surveyed points will have to be marked clearly by stakes, for example. In the event of a quick test-site change, all geographic positioning information will then be readily available.

The general location of the control van, the weather station, the electric power station (if necessary) also have to be determined in advance. Optimum layout of cables from microphones to the center recording station and other electric cabling should be planned for all of the potential sites.

If not already short enough, the grass at the test site, where the microphones are positioned must be cut (by means of a lawn-mower or, environmentally much more acceptable, by means of several sheep) shortly before the test.

(b) Equipment Set-up

Setting up Acoustic Instrumentation / Central Acoustic Control Van

All required microphones (i.e. microphone cartridge, dehumidifier, preamplifier) must be set up at the predetermined locations on their microphone stands at a height of 1.2 m above the grass surface (Fig. 3.41a). Since grass is not a well defined surface, deviations from the nominal 1.2 m are unavoidable. As had been stated before, this fact is particularly bad for propeller-aircraft tests and to a lesser extent for helicopter tests. For Chapter-10 type tests the microphones are invertedly positioned on the hard-solid round plate (Fig. 3.41b). Hence the position is much less critical and acoustically better defined.* For research purposes - to be distinguished from certification type measurements - one would certainly prefer the ground-proximity arrangement, or alternatively the microphone(s) to be positioned about 10 m above the ground as shown in Fig. 3.41c.

* It should be mentioned that ICAO encourages noise certification testing to be conducted with both microphone arrangements (1.2 m and "0" m above ground) to establish a broad data base for an eventual decision on using one or the other microphone position for other ANNEX-Chapters than Chapter 10

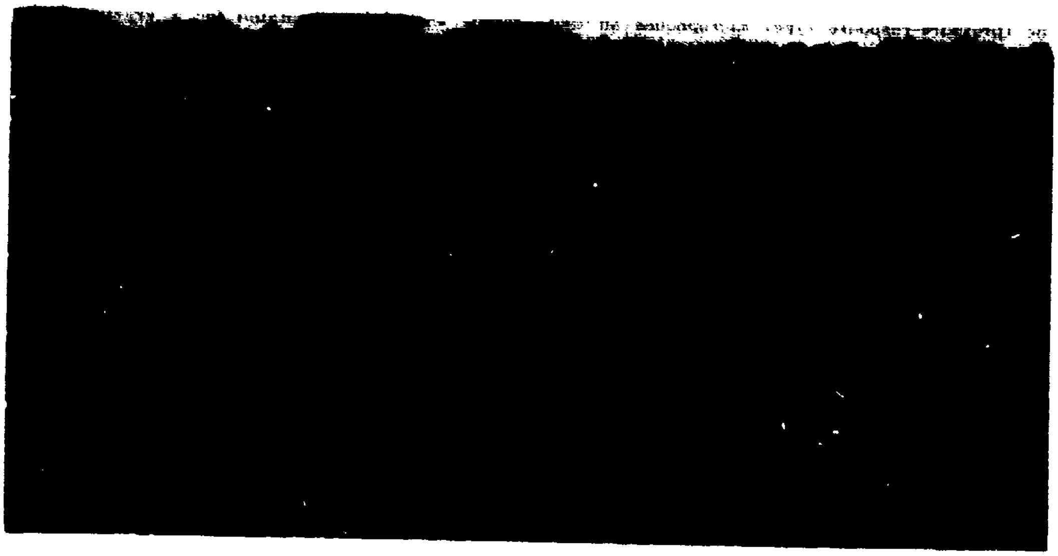


Fig. 3.41a Microphone with wind ball on 1.2 meter high stand

Fig. 3.41b Inverted microphone configurations (left: early version; right: specified version)

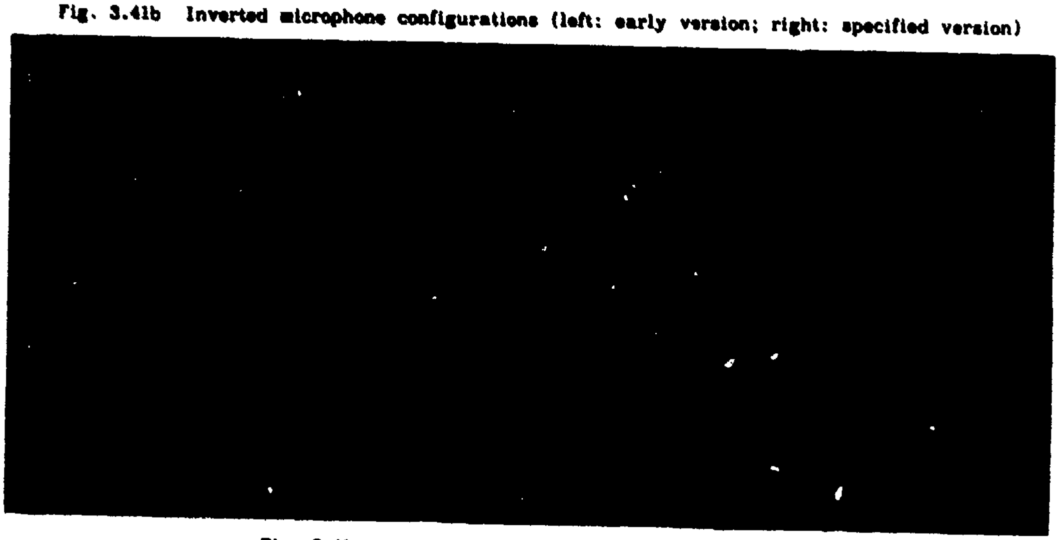


Fig. 3.41c Microphone array on 10 meter high poles

The (pressure-response type) microphones on their stands should be orientated for a grazing incidence direction. The microphones must be covered by a polyurethan foam wind-ball (to be temporarily removed for pistonphone-calibration). The microphones are then connected by extension cables (3 m to 10 m long each) to their power-supplies (if non-prepolarised condenser-microphones are used) and switched on to allow for a sufficient "warm-up" time.

The power supplies themselves should have a protective housing, to provide some shielding against sunshine and unexpected drizzle (in which case the microphones could also be temporarily covered with a plastic bag for protection). Thereafter, the signal cables (up to 800 m long, usually of the BNC-type) are rolled out to provide the connection between the power supplies and the signal conditioning instrumentation.

Depending on the microphone sensitivity, the type of aircraft and its expected closest approach to the microphone, the wideband RMS signal voltage from the preamplifier might range from 100 µV to 1 V; this 80 dB range must be adjusted prior to recording, such that the maximum voltage (accounting for crest factors and the impulsivity of the expected signal, see Section 3.2.3) is close to the preferred value. Such adjustment can be achieved by using a precision sound level meter (PSLM), being a low-noise, wide-band signal conditioner with low distortion.

Maximizing the electric signal-to-noise ratio requires continuity of the electrical shielding from the preamplifier all the way to the input of the PSLM. As radio signals can be picked up, the shield should be grounded at the tape-recorder end of the signal cable by an insulated wire, so that contact with the metal structure of the control van (which houses the tape-recorder and the PSLMs) is avoided.

Each microphone/power-supply data channel is connected to its own PSLM, which in turn is connected to the multi-track tape-recorder input. As stated above, PSLMs and the tape-recorder should be located inside the central control van or container for operation by the acoustic test engineer. T-connectors are used to connect peripheral instrumentation, such as one or several graphic level recorders (to monitor flyover A-weighted pressure-level time histories). Oscilloscopes, preferably one for each channel are very useful for monitoring each microphone output, as each microphone receives its own transient signal, not necessarily identical to those of other microphones (especially of side line microphones).

Precision sound level meters and research-type tape recorders are equipped with overload indicators to allow adjustment of levels on the signal conditioning instrument. If an A-weighted signal is to be recorded directly, then the input-attenuator will be adjusted for maximum wide-band, <u>unweighted</u> signal strength, and the output-attenuator for maximum wide-band <u>weighted</u> signal strength. This is not normally done, unless a Chapter-6 or Chapter-10 type measurement is carried out, or if dynamic range compression is important. In all other cases, and especially when an EPNL-value must be determined, the unweighted wide-band signal is recorded.

At each acoustic measurement station a pistonphone, preferably one that is capable of generating several discrete-frequency tones (e.g. 250 Hz, 500 Hz, 1000 Hz), should be available. In addition it is advisable to employ a pink-noise generator to check the entire frequency response in the field. If distances between individual acoustic measurement stations are not too large, "hand-carrying" a calibrator (discrete, or wide-band, to the various stations eliminates whatever slight differences might exist between individual calibration equipment.

If relatively few microphone stations (e.g. 3) are used each data channel can be equipped with its own PSLM. If many microphones are used (e.g. 6 or more) the use of individual PSLMs would be a rather expensive undertaking and use of a multi-channel signal conditioner would be a better approach.

If many channels are to be recorded and monitored, it is impractical to write down all gain-settings for each channel manually, especially if gain settings have to be changed frequently for successive flights at different heights. In that case, a gain-setting printer should be connected to the signal conditioner.

In addition, a head-set monitor should be connected to the PSLM output or to an appropriate output connector on the tape recorder. This is helpful for the test engineer to acoustically monitor incoming signals "by ear", since - if inside the control van - he would not normally have visual or acoustic contact with the approaching test aircraft. Also, the voice-microphone for annotation on the cue-track of the tape recorder would have to be activated with a switch to allow the alternate recording of a voice annotation and the time-code-generator signal on that same track.

If only one multi-track tape recorder is used, synchronization between the acoustic measurement station(s) is no problem. If, however, several autonomous acoustic measurement stations are used, each station constitutes an entity in itself that must be set up individually. Typically, the PSLM, the (2- or 4-track) tape-recorder, and the graphic level recorder will be placed on some field-lab table with a protective shading-umbrella some distance (10 m to 15 m) away from the microphone/power-supply assembly to ensure the 75° or 80° non-reflecting cone around the microphone vertical. The only difference then is that time synchronization between tape-recorders must be established, as will be discussed in the following sections.

Setting up Time Synchronization

Time synchronization must be established between the various acoustic measurement stations, the aircraft tracking stations, the meteorological stations and the aircraft cockpit and - if applicable - the air traffic control tower. Although Universal Time (UTC) or Greenwich Mean Time (GMT) are continuously broadcasted by radio-stations in America and in Europe, these signals are influenced by electromagnetic disturbances with ensuing variations in signal-to-noise ratio. There are, however, geostationary satellite systems from which signals from a ground station are relayed back to ground. In the United States these are continually synchronized with the National Bureau of Standards time. The equivalent in Europe is synchronization with the time standard of the German 'Physikalisch-Technische Bundesanstalt'.

This time signal can be encoded for recording on a tape-track using an appropriate format, such as the IRIG ("Inter-Range Instrumentation Group") time code. The "IRIG Time Code B" is most widely used for aircraft time synchronization. It uses a 1000-Hz carrier frequency with a 1-second time frame containing 100 tone-bursts to provide a resolution of 1 ms. The radio receiver in the control-van can pick up the signal and convert it to an amplitude-modulated 1000-Hz-wave. The master tape-recorder, the autonomous tape-recorder stations and the tracking stations must each have their own time-code generator. A portable time-code generator - synchronized with the master time code generator in the control van - can then be carried to each measurement station for initial, and also for subsequent repeated synchronization among all the time-code generators used. A time code reader will be required for data processing later.

Establishing Radio-Communication

The following radio-communication links with one, two or three specially licensed receive/transmit VHF channel frequencies (in the 50 MHz to 300 MHz range) should be available for transmission

- from the control-van to the test aircraft and to the meteorologial aircraft and vice versa;
- from the control-van to the acoustic, the tracking and the meteorological stations and vice versa;
- for the ground personnel amongst themselves;
- from the control-van to the air-traffic control tower and vice versa.

The following receive-only links would be required, in order to monitor (on existing frequency bands)

- communication between test aircraft and tower;
- communication of air traffic control;
- communication of ground traffic control.

Hence, appropriate special radio-communication equipment is to be set up in the control van, in the test and meteorological aircraft and at the various outbound stations.

Setting up Tracking Equipment

Special requirements are to be observed in setting up any mobile tracking equipment. Independently of which system is used (e.g. kinetheodolite, laser, or tracking radar) its position with respect to the geo-stationary coordinate system must be carefully determined. Also, careful leveling and determination of systematic errors is paramount, since deviations of the order of fractions of a degree will result in gross tracking errors. Such errors might result from boresight axis collimation errors, range bias, and leveling misalignment. All these should eventually be taken into account in the evaluation process.

If permanently installed systems are available, say near airports, the important coordinates are already precisely known. If mobile or portable systems are used, coordinates can be freely selected; to facilitate the trajectory data analysis in case of a take-off or landing flight procedure, it would then be advantageous to select the coordinate system (in which data are presented) to coincide with the runway center line, and a line vertical to the runway center line.

Modern trajectory measurement systems such as kinetheodolites and tracking radar are usually equipped with time synchronisation. If, for example, several kinetheodolites are used in a certification test it is advantageous to synchronise both by triggering them at regular intervals utilising the same time base. The trigger pulse could then also actuate a film-frame counter in each kinetheodolite, such that each frame number would now also be a measure of time.

Since precise time synchronisation is of the utmost importance for tracking, the time-instances of shutter-operation (if still-picture cameras are used) must be relayed to the master tape recorder by means of signal cables or by radio. Likewise, kinetheodolite time signals for each of the film-frames must be transmitted. If continuous tracking by laser or radar equipment is used, the time-code signal is recorded and plotted in real time with the flight-trajectory coordinates. Laser or radar equipment will usually be several hundred meters away from the ground track and will therefore not constitute a reflecting surface to be concerned about.

Setting up Meteorological Equipment

For ease of handling, a 10 m high weather mast - usually consisting of several telescopic sections to be cranked up towards full length - is often mounted on a trailer. Telescopic configurations provide good mechanical stability; otherwise stabilising wires will be necessary. The weather mast should be positioned close to the measuring microphones (but not too close because of possible reflections) and some distance away (100 to 200 m) from the (heat-producing) control-van. The meteorological measuring instruments should operate continuously from the start of the day, so that any gross changes in atmospheric conditions during the actual testing will be immediately apparent.

Weather stations close to the ground are somewhat easier to handle. ANNEX 16 requires that for Chapter-6 and Chapter-10 type measurements atmospheric information be gathered at 1.2 or 2 m above ground.

If meteorological data aloft are measured by a tethered radio sonde, its launch station should be prepared in advance of the test. This station should again be sufficiently far away from the central acoustic measurement station to avoid noise contamination and reflections.

Setting up an Approach Guidance System

Landing-approach noise tests where a specified descent angle must be maintained precisely require excellent ground based guiding systems for the pilot. For helicopter approach noise tests, a frequently used method involves the operation of two "Precision Approach Path Indicators (PAPI)". The type 2/Mark 5 of the BARREL LIGHTING Co. Ltd. (Fig. 3.42) is a portable version of such a PAPI. This particular instrument projects two beams of light towards the approaching aircraft. The two projection lenses are arranged in the vertical; here the top light-beam is white, the lower one red.

Fig. 3.42 Precision Approach Path Indicator "PAPI" (Barrel Lighting Co)

For visual pilot guidance two PAPIs are required. The two units are arranged to the left and right of the approach path centerline, equi-spaced several meters (e.g. 5 m) to either side of the approach-path/ground-plane intersection. One unit is adjusted vertically, such that the red/white boundary is at the lower limit of the desired approach angle (usually 0.5° from the nominal, e.g. 6.0° - 0.5°), the other unit at the higher limit (e.g. 6.0° + 0.5°)

The approaching pilot will then see one red light and one white light if he is within the glide-slope limit; he will see two whites, if he is too high; he will see two reds, if he is to low. Following these guide-lights, the pilot can now readily adjust his descent-slope to within the limits of the selected glide slope.

The two PAPIs must of course be aligned in the direction of the flight track. This alignment is not very critical and may be done "by eye" using for example the center microphone position as a reference. Aligning the units in the vertical plane must be done much more carefully. This is achieved with a built-in inclinometer which is accurate to one or two minutes of arc. Also, the PAPIs must be mounted on a rigid support. If this support structure is laid on soft ground, it may sag in the course of time. A misalignement by 1 or 2 degrees will already produce significant errors in the results. It is, therefore, advisable to check the alignment frequently.

Westland Helicopters Inc. |20| has shown that the actual approach angle can deviate by much more than 0.5 degrees when such a PAPI is used, as illustrated in Fig. 3.43. Although the PAPIs are aligned to 9 +/- 0.5 degrees, the dotted lines show that the actual approach angle can actually vary between 8 and 10 degrees even when the PAPI indicator otherwise works perfectly correct throughout the aircraft approach.

This shows that a PAPI-system is really not capable of meeting the most stringent tolerances that are required at present.

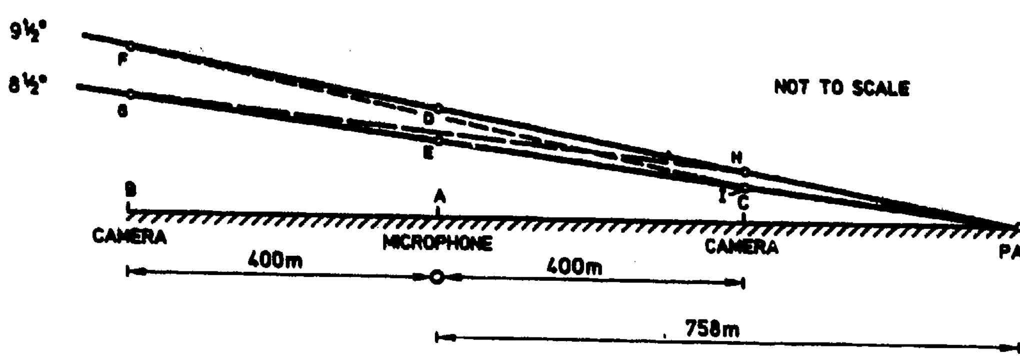


Fig. 3.43 Possible flight path deviations of between 8.0° amd 10.0° with double PAPI system set at angle 9.0° +/-0.5°

The Control Van

The control van, housing the master control and communications center, will contain all acoustic recording and in-the-field analysis equipment, the time-synchronisation equipment and the read-outs for meteorological information. The test engineer is in radio contact with each autonomous acoustic measurement station, with each tracking station, with the pilot and observer in the test aircraft and, as the case may be, with the air traffic control tower. It may be necessary to air-condition the van, not so much for personnel comfort but for equipment temperature reliability.

3.5 Test Execution

The details of the noise certification test will to some extent depend on the type of aircraft (fixed wing propeller, fixed wing jet, or rotorcraft) and on the particular procedure (take-off, level fly-over, approach). In general, however, noise certification tests have much in common, and the procedural aspects as discussed below are essentially relevant to all types of aircraft noise testing. As stated above, data to be taken fall into the four following categories

- acoustic,
- aircraft operational,
- aircraft tracking, and
- meteorological.

Prior to all testing, a well thought out and sufficiently detailed test plan and test matrix must be established and distributed to all concerned. Also, a thorough pre-test briefing must be held, so that everybody fully understands what is required and what are his or her specific tasks. Specifically, the ground test crew (acoustic, meteorological, and tracking) and the test pilot and the observer must be thoroughly informed.

3.5.1 Acoustic Data Acquisition

(a) Tape Selection

Enough high quality, low-noise tape to cover the entire expected test duration should be readily available. The typical 14-channel tape-recorder requires 1-inch tape, which comes in reels of 8, 10, 12, and 15 inch diameter. In a typical aircraft noise test the highest frequency of interest will be at least 10 kHz, more often 12.5 kHz; the tape speed should then be no less than 15 in/s. It is desirable to employ long tapes to eliminate frequent changes during a test. Changes will not only require recalibration but can also jeopardize comparability, as there are differences in the electromagnetic properties of tape of up to 1 dB. For each tape these must be determined through prior calibration.

If several autonomous 2- to 4-track tape-recorders are used instead of one central multi-channel tape-recorder, these would typically take 1/4-inch tape. Again, the tape-speed will be dictated by the frequency range of interest, although now the tape-length is much less, requiring more frequent tape-changes. It is good practice to start all individual tape recorders simultaneously with a new reel, so that changing the reels can occur on all tape-recorders at the same time. The necessary calibrations can then occur simultaneously while the flight test is interrupted.

(b) In-the-field System Calibration

All electronic equipment, i.e. microphones, power supplies, precision sound level meters, tape-recorders, graphic level recorders, monitoring oscilloscopes and analysers (if used in the field) should be switched on at least 15 minutes or better still one hour prior to the start of testing to allow for a sufficient stabilization-period.

The measurement chain in its entirety should then be calibrated by means of (preferably only one) pistonphone for discrete frequency (sinusoidal) response at - if possible - several frequencies. The pistonphone is slipped over the (live) microphone cartridge after removing the wind-ball and held there by (a steady) hand, while each calibration tone is recorded for a period of 15 to 30 seconds. The gain settings should be written down and annotated on the voice track. It should be remembered that the output of a pistonphone depends on the ambient pressure which must therefore also be recorded.

An in-the-field pink-noise calibration for overall frequency response is also advisable, if only to check whether the system response has stayed the same since the preparatory laboratory calibration. In that case the pink-noise generator will be connected to a dummy-microphone after removing the microphone cartridge and a recording made on the data tape track.

In addition to recording the pistonphone signal, its level should also be monitored at instruments within the measurement chain, notably at the sound level meters and at the indicator instrument on the tape recorder.

Such calibrations should be repeated at appropriate time intervals; in any case, however, at the beginning and at the end of each data tape and, for long tapes, even in between.

(c) Ground-crew Briefing

On the basis of the test matrix, the test engineer will brief each of the ground crew members about the sequence of events prior, during, and after each flyover occurs. It should in particular be made clear how the approaching aircraft will be announced, how gains must be set on the instruments, how the test must be annotated on each of the tape-recorder voice tracks, what information should be written down (preferably on prepared note-pads), when to switch the instruments on and off, when and how calibrations should be conducted and what kind of immediate response is expected right after the flyover.

Similar briefing information must be given to the tracking personnel.

(d) Noise Recording

Each noise test requires a sufficiently detailed test matrix, available to all test participants, including the pilots. A test-number must be assigned to each test, to be mentioned on the voice tracks of all tape-recorders prior to the event.

As had been discussed in previous sections, it is of great importance to ensure adequate gain settings for all instruments, taking into account the characteristics of the expected signal.

Obviously, a sufficiently large margin below the overload condition is always necessary; however for a predominantly broadband signal, such as for a jet-propelled aircraft, a small margin will suffice while for a strongly impulsive sound type, such as from a helicopter under a blade slap condition a larger safety margin will be required.

Preferably, the optimum gain setting for each acoustic measurement station should be determined during prior test flights. Such preparatory flights are usually made anyway, as the pilot will want to practice the test procedure. If that is not possible, estimates of the expected sound level could serve to initially adjust the gains. The levels to be expected can often be taken from tests on similar aircraft. As a very coarse guide-line the following figures can be used: a light propeller-driven aeroplane at 300 m height would produce between 70 and 80 dB(A), as will a helicopter at a flight height of 150 m.

The corresponding levels for subsonic jet aircraft may range somewhere from 80 to 90 dB, for flyover, sideline and approach (Note, that these are A-weighted levels, which are of interest in setting the gains in the field, rather than any EPNLs, which do not allow a gain setting in the field!).

Immediately before the actual test flight, the test engineer should announce the upcoming test number, the direction from which the aircraft will approach the measurement stations (if a "to-and-fro" type flight test takes place) and should check with each of the outside stations to make sure they are ready for data recording; he should also check whether the pilot is ready, and alert, as the case may be, the air-traffic control tower about the upcoming test flight. If everything is ready, the test-pilot gives a warning just before the beginning of the test. The test engineer will then alert all test stations (including the tracking stations) and issue the command to switch on all recording instrumentation.

The recording should start well before the noise from the approaching aircraft emerges from the background noise and should continue until the aircraft noise is well below the background noise, as illustrated in Fig. 3.44. This practice also provides an indication of the background noise, which should be carefully monitored by the test engineer. The broadband (unweighted) noise signal should at the very least exceed the broadband background noise by 15 dB. This must be considered to be marginal, since the "10-dB-down points" must be at least 5 dB above the ambient noise. It should be recalled that for the EPNL-computation the 10-dB-down-points of the 'maximum tone-

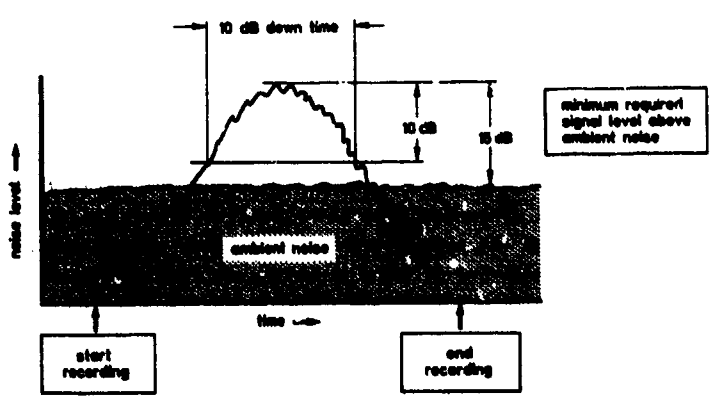


Fig. 3.44 Recording time sequence

corrected Perceived Noise Level', PNLTM, are required for data-processing (see Appendix A to this AGARDograph). If the difference between (the readily available) maximum A-weighted signal level and A-weighted background noise becomes less than 15 dB during the test, then the test engineer must decide whether to continue or to terminate testing. Prior to recording the flyover noise the engineers at each of the autonomous acoustic measuring-stations should annotate on their tape recorders the upcoming test number, the time, the flight direction (e.g. East-West, or flight direction 27, or approaching from such and such a land mark) and all gain settings on the sound level meters (or whatever signal conditioning instrument is used). Redundancy of information is certainly good practice! After the test aeroplane has overflown the measurement stations, each of the outside test engineers must report to the control van that the aircraft flyover noise has submerged into the background noise and wait for the command to switch off. The test engineer then inquires at each outside station about the acceptability of the data and the occurrence of any problems. He would further ask the test pilot on board, if engine and other flight operational parameters have been within specifications. If tracking information is readily available, e.g. when a polaroid picture or a real-time laser tracking are used, he can then proclaim the flight a "valid one", and - unless a sufficient number of valid flights have already been flown - call for the next test flight. The test aircraft would then either prepare for an approach of the measurement station from the other direction (if it was a level flyover) or intercept whatever climbing or descending flight path was specified in the test.

3.5.2 Flight-operational Considerations

(a) Pilot Briefing

The test pilot must know the required settings of engine parameters and the flight trajectory to be followed. The following should be considered as a typical pilot briefing pertaining - in this case - to a Chapter-8 helicopter noise certification test. Here the pilot is informed about the details of the take-off procedure, the level flyover procedure, and the landing approach procedure (for reference see Section 2.7). His (written) instructions will include the following information:

- Take-off procedure:
  - approach the rotation point at an altitude of 20 m (66 ft);
  - maintain a stable airspeed of V_y +/- 3 knots throughout the entire flight;
  - maintain a stable rotor speed at maximum (top of green arc) normal operating RPM;
  - begin climb-out with take-off power at the designated marker, maintaining the prescribed stabilised airspeed and rotor-RPM;
  - continue the stabilised climbout until informed by the test engineer that the test is over.

- Level Flyover:
  - pass over the center-line microphone at a height of 500 ft;
  - stabilise airspeed at 90% V_H;
  - stabilise rotor speed at maximum normal operating RPM (top of green arc);
  - maintain these conditions from 500 m before to 500 m after flying over the center measurement station.

- Landing Approach:
  - maintain a steady approach angle of 6°+/-0.5° as indicated by the PAPI-system;
  - stabilise airspeed at V_y;
  - stabilise rotor speed at maximum normal operating RPM (top of the green arc);
  - commence approach at 750 ft above ground level and continue until reaching 100 ft above ground level.

(b) Co-Pilot/Observer Briefing

Unless the certification test involves a very small, light propeller driven aeroplane such as a powered glider there will usually be an observer to assist the test pilot. The observer will monitor cockpit-instrumentation data. In the case of a helicopter there will be torque, rotor-RPM, indicated airspeed, outside temperature, indicated rate-of-climb or descent and flight altitude (although on-board altitude-information is not used for data evaluation, it should be recalled that ANNEX specifies an aircraft independent flight-height determination). The observer will further monitor the fuel-gauge to warn when the aircraft weight drops below a critical value.

All this information, identified by the test number and the time corresponding to the flyover-instant above the central measurement station should be written on a note-pad. A typical page from such a note pad of a helicopter noise test is reproduced in Fig. 3.45. It shows columns for run-number, time, weight in terms of fuel remaining, indicated airspeed, rotor RPM, torque (in terms of % of the maximum), flight altitude, rate of climb or rate of descent, outside temperature, as well as a column termed "Remarks". This latter column can be very valuable in the data evaluation process. For example, observer remarks such as "cross wind too high", "lots of turbulence; speed build-up slow", "bumpy over center mike", "badly stabilized, lots of control req'" etc. are quite helpful in the later interpretation of data.

DATE: [illegible]

RUN NO.	TIME	FRAME COUNT	AUW lbs/kg	IAS kph	ROTOR RPM	TORQUE %	ALTITUDE AGL ft.	RoD/ROC ft/min	OAT C	REMARKS
B, 12	0947	622/863	350	—	—	—	—	—		overflying noise
B, 13	0958	642/827	330	120±2	100	82	460			ok
B, 14	0955	674/873	325	120±2	100	78–82			+19 [illegible]	ok.
B, 15	0959	705/800	310	120±2	100	76–83				ok
H 1	1039	785/887	230	125	100	85			[illegible]	[illegible] 220 1017.
H 2		771/593								too noisy
H 3	1047	774/893	225	125 / 123	100	85				[illegible] little [illegible] 50' maybe.
H 4	1050	809/901	210	124	100	85				quite a lot turb preventing speed building up
H 5	1052	[illegible]	205	125	100	85				
A 2. 1	1116	873/912	475	66±3	[illegible]	100		900		[illegible]
A 2 2	1118	932/932	470	66	100 / 99	100		1000		bumpy over centre mike. thermal off runway?
A 2 3	1120	936/929	465	66–70	100 / 99	96–100		1100		

Fig. 3.45 Typical "flight log" as generated by observer/co-pilot

Instead of writing down information, a camera is often used to take pictures of the cockpit instrumentation at predetermined time intervals or following specific commands from the test-engineer on the ground. More conveniently, pictures can be obtained automatically either by means of a cine-camera taking a picture every 1/2 or 1 second or by a video-camera. Time-information should appear on the picture frames.

(c) Weight Watching

If, for whatever reason, many more test flights are required than specified as minimum number it may be necessary either to refuel or to add ballast if the specified flight mass falls below the allowable minimum mass (e.g 10% below maximum). In a medium-weight-helicopter test, for example, it can be necessary to add ballast (such as lead-granulate bags) every hour of flight time and to refuel every third stop to maintain the specified flight mass.

3.5.3 Meteorological Data Acquisition

Depending again on the technical sophistication of the test, ground-meteorological data from a 2-m or a 10-m pole are either recorded automatically or are written down from visual readings. Since a too high wind speed or cross-wind component will invalidate the test flight, such information must be readily available to the flight test engineer. Hence the 30-second average wind-speeds must be noted at the instant of flight over the center measuring station. A typical note-pad page is reproduced in Fig. 3.46, showing columns for time, run-number, relative humidity, air-temperature, wind-speed, wind direction, flight direction and cross-wind speed. Similar listings would be made for air-pressure; there readings every 15 minutes would suffice.

B.S.T.	RUN N°	RH %	TEMP °C	WIND SPEED knots	WIND DIRECT deg	FLIGHT DIRECT deg	CROSS WIND knots
9.58.30	R.1.2	76.6	18.8	2.7	271	27	+2.4
10.02.00	R.1.3	72.0	19.1	2.8	253	.	+2.0
10.04.45	R.1.4	70.8	19.3	4.2	248	.	+2.8
10.08.00	R.1.5	71.0	19.2	3.8	260	.	+3.3
10.11.15	R.1.6	70.3	19.1	1.9	290	.	+1.9
10.23.15	P.1.1	67.3	20.2	3.5	263	.	+2.9
10.31.30	P.1.2	65.8	20.5	3.5	281	.	+3.4
10.34.30	P.1.3	57.2	20.5	5.0	280	.	+4.8
10.38.00	P.1.4	51.4	20.8	3.0	286	.	+2.9
10.41.45	P.1.5	53.1	21.3	6.2	269	.	+5.5
10.45.30	P.1.6	53.1	21.5	5.1	296	.	+5.1
12.07.00	R.2.1	44.3	22.0	9.1	330	.	+7.6
12.11.00	R.2.2	43.8	23.3	5.8	299	.	+5.8
12.15.00	R.2.3	41.4	22.1	4.9	329	.	+4.3
12.17.45	R.2.4	41.9	22.4	5.0	304	.	+5.0
12.22.00	R.2.5	42.2	22.4	5.1	293	.	+5.1
12.25.45	R.2.6	43.5	22.5	5.2	255	.	+3.9
12.31.30	R.2.7	42.6	22.4	5.1	288	.	+4.9
12.34.45	R.2.8	43.0	23.3	4.3	339	.	+3.2
12.40.45	P.2.1	46.7	22.7	8.6	265	.	+7.3
12.43.45	P.2.2	42.5	22.6	7.7	252	.	+5.4
12.48.00	P.2.3	42.1	23.1	5.0	285	.	+4.9
13.34.15	P.2.4	41.1	22.7	3.4	164	.	-2.3
13.37.15	P.2.5	40.4	23.7	5.5	260	.	+4.4
	P.2.6	aborted					
13.41.30	P.2.7	39.7	24.2	6.6	246	.	+4.2

Fig. 3.46 Typical note-pad page from meteorological ground station

3.5.4 Aircraft Tracking

To establish the validity of a test flight, it is also important to have flight trajectory information available to the flight test engineer in "real time". As had been discussed previously, the laser-tracker and tracking-radars are the only systems that provide such information instantaneously. Such sophisticated tracking methods (as described previously in Section 3.3.1 where e.g. onboard processors provide ad-hoc guidance on the flight path for the pilot) can be, and normally are, used in any comprehensive and involved noise certification tests of, say, subsonic jet aircraft or heavy propeller-driven aeroplanes. A less sophisticated method that provides almost instantaneous information is the polaroid-backed still-picture camera; the camera-operator can determine the height of the aircraft by means of a magnifying-lense reticle reading. This can be achieved within one or two minutes (since development of the instant picture takes between 1/2 and 1 minute, depending on the outside temperature). This is actually quite long, since a helicopter or a light propeller-driven aeroplane can turn for the next test-flight in less than that time span. Still, the other systems, such as kinetheodolites, require off-line processing. It is, therefore, a good idea to have at least one polaroid-camera, redundant to the other tracking-equipment, to provide instantaneous tracking information.

Tracking provides - among other things - information on ground speed, an important input to compute the EPNL. The true airspeed determined from on-board instruments, on the other hand, is an important parameter to compute Mach-number and the advancing, or helical blade tip Mach-numbers for helicopter rotors and aircraft propellers.

3.6 Data Analysis

This section describes the post-test analysis of the acoustic data, specifically the determination of either a 'maximum A-weighted flyover noise level', as required for the noise-certification of light propeller-driven aeroplanes (ANNEX Chapters 6 and 10), or an 'Effective Perceived Noise Level' for helicopter, heavy propeller-driven aeroplane and subsonic jet-aircraft (ANNEX Chapters 8 and 3) noise certification. In the course of this Section, it will be demonstrated how tracking and meteorological information is utilized to correct flight noise data towards reference conditions.

3.6.1 Data Analysis - Determination of the Certification maximum A-weighted Flyover Noise Level

The first acoustic information available after completion of a test series is probably the A-weighted flyover noise-level time history as measured in the field at each measurement station. A typical recording appears in Fig. 3.47. In addition a plot of the typical background noise - also weighted - should exist, such as shown in Fig. 3.48. These recordings are immediately inspected visually for any evident non-test related disturbances, as might result from wind gusts or extraneous noise sources. Next, one would check if the flyover signals were sufficiently above the ambient noise level. In the case of a Chapter 6 or Chapter 10 noise certification test, a 10 dB signal-to-noise ratio will usually suffice. The maximum levels that occurred during the flyover must then be corrected to establish the final noise certification level. These corrections are quite easy to perform for the Chapter-6 test but somewhat more involved for the Chapter-10 test.

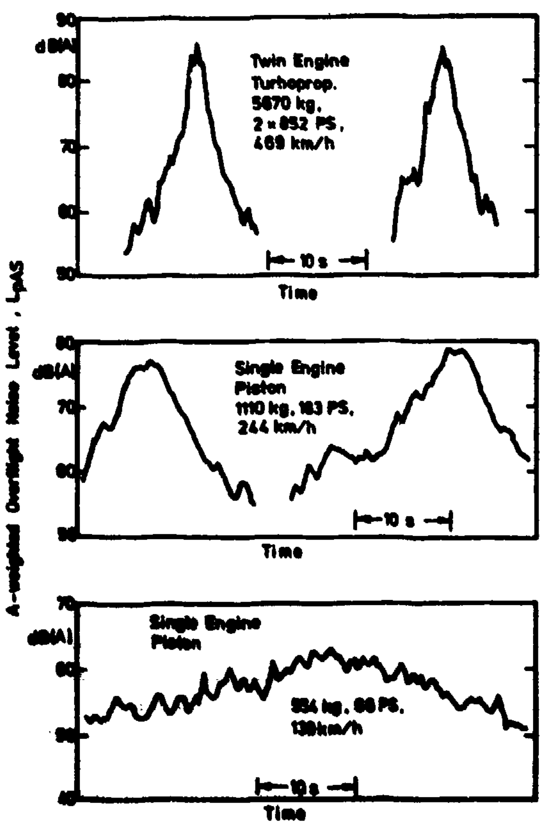


Fig. 3.47 Flyover A-weighted noise level time histories for propeller-driven aeroplanes of different take-off mass and engine powers at a flight height of 300 m

Rather than visually reading these maximum levels from a graph like Fig. 3.47, all the "good" recordings are usually replayed through a laboratory-based precision sound level meter. The maximum levels are

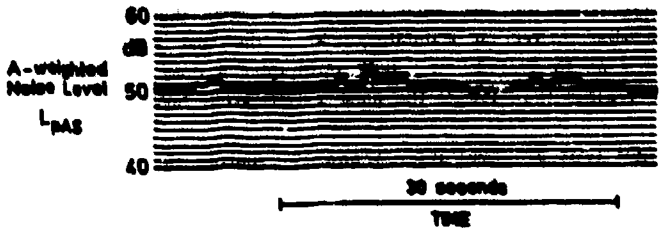


Fig. 3.49 Time history of typical daytime ambient A-weighted noise level ("background noise")

then read from a peak-hold digital instrument, or, if such an instrument is not available, from an analog indicator instrument. These measured maximum levels and the associated aircraft operational and meteorological information for a minimum of 4 (Chapter 3) or 6 (Chapter 10) valid flights are then used in an assessment of the confidence-limits as specified in the ANNEX 16.

(a) Chapter 6 Test (See Section 2.5 of this AGARDograph)

Flyover $L_{pA,max,slow}$-values must be corrected for deviations of the test helical blade tip Mach-number from their reference values which are due to deviations from the reference temperature. No height correction is required if the test aircraft was within +10m/-30m of the reference height; also, atmospheric absorption need not be accounted for, since the test must be conducted within the temperature/relative humidity window shown in Fig. 2.16.

The following example of a Chapter 6 Test is to illustrate the procedures. Let us assume that the test environment and aircraft operational characteristics were

Propeller diameter	= 2.0 m
Reference propeller RPM	= 2700 min^{-1}
Reference flight speed	= 200 km/h
Reference temperature	= 25 °C
Reference flight height	= 300 m

From this, one computes a reference helical blade tip Mach number of 0.832.

TABLE 6 below lists (hypothetical) measured noise levels, test-flight operational parameters, and test environmental conditions. The operational and environmental parameters deviate from reference. They are, however, all within the allowable test windows. Recall that the temperature window was 2 °C to 35 °C, and the height window was 270 m to 310 m.

TABLE 6 Example of Data-Sheet for a Chapter-6 Noise Certification Test (T_{ref} = 25 °C, M_{ref} = 0.832)

Test Nbr	L_{pA} dB	V_{oo} km/h	RPM 1/min	T_T °C	H_T m	M_T	M_R-M_T	Δ2 dB	$L_{pA,corr}$ dB
1	78.2	210	2690	33	305	0.820	0.012	0.9	79.1
2	75.4	195	2650	25	275	0.817	0.015	1.2	76.6
3	77.9	205	2710	27	290	0.833	-0.001	0.0	77.9
4	77.2	200	2700	31	295	0.824	0.008	0.6	77.8
								$\bar{x}$	78.1
								s_x	1.6
								u_p	1.35

Tests 1, 2, and 4 show significant deviations of the helical blade tip Mach number, as is evident from the column $M_R - M_T$. In all these cases the test Mach number was lower than the reference Mach number, thus making a Mach-number correction mandatory. When the test Mach-number is higher than the reference Mach number - as in Test 3 - , ANNEX 16/Chapter 6 does not prohibit a correction, since this could only raise (rather than lower) the noise certification level.

If no results from noise sensitivity flight tests are available, ANNEX 16 requires the addition of a factor Delta 2 = 180 log M_R/M_T; this factor is also listed in TABLE 6. The corrected levels in the right-most column are arithmetically averaged, to produce a final average level $\bar{X}$ = 78.1 dB(A) with a standard deviation of s_x = 1.6 dB. For a sample of N = 4 data points and accordingly N - 1 = 3 degrees of freedom TABLE E-1 in Appendix E lists a Student-factor $t_{4;0.10}$ of 2.353, corresponding to a 90% confidence limit of 1.35 dB. As this value is still less than the permitted value of 1.5 dB, the flight test produced a valid noise certification level.

This example illustrates a Chapter 6 noise certification procedure which requires a performance correction. If the aircraft had the operational capabilities of the example of Section 2.5.7, a Malus of 1.2 dB is added to the above noise certification level. This would then lead to a performance-corrected value of 79.3 dB(A), just below the permitted 80 dB(A), if the aircraft had a take-off mass in excess of 1800 kg. Hence, the aircraft would have passed the noise certification test.

In the above example it was tacitly assumed that the environmental temperature/relative-humidity conditions were within the permitted area shown in Fig. 2.16 and that the wind-conditions were acceptable.

(b) Chapter 10 Test (See Section 2.6 of this AGARDograph)

A (take-off) Chapter 10 noise certification test data reduction will require an atmospheric absorption correction (under certain conditions), a height correction, a helical propeller blade-tip Mach number correction and an ambient pressure correction.

While Chapter 6 requires a level flyover, Chapter 10 involves a take-off. Here, the operational parameters of the test aircraft at the reference atmospheric conditions exactly define the flight trajectory; hence no performance correction is necessary. Suppose that the test aircraft in the previous example has to be tested according to Chapter 10. Then a minimum of 6 valid test flights are required. TABLE 7 below gives a list of (hypothetical) measured data.

TABLE 7 Example of Data-Sheet for a Chapter-10 Noise Certification Test
(T_{ref} = 15 °C, M_{ref} = 0.847)

Test Nbr	L_{pA} dB	V_y km/h	RPM 1/min	T_T °C	H_T m	M_T	M_R-M_T	ΔM dB	Δ1 dB	Δ2 dB	$L_{pA,corr}$ dB
1	78.2	210	2690	33	305	0.820	0.027	0.5	[illegible]	2.1	81.9
2	78.4	195	2650	25	275	0.817	0.030	0.5	1.2	2.3	78.4
3	77.9	205	2710	27	250	0.833	0.014	0.5	1.6	1.1	80.1
4	77.2	200	2700	31	295	0.824	0.023	0.5	1.8	1.8	80.3
5	75.4	215	2750	32	300	0.840	0.007	0.5	1.9	0.5	78.3
6	79.1	190	2630	35	280	0.811	0.036	0.5	1.3	2.8	82.7
										$\bar{X}$	80.3
										s_x	1.8
										u_p	1.47

Recall that for this test, the reference temperature is 15 °C. Then the reference helical blade tip Mach number is 0.847. Suppose that the reference flight height (during climb!) above the acoustic measuring station was 240 m, i.e. much less than the one actually flown during the test (perhaps due to some head-wind). The test day average relative humidity is taken as 80%. On account of the observed temperatures, all tests were <u>outside</u> the atmospheric 'no-correction'-window. ANNEX 16/ Chapter 10 then requires a Delta M correction. For a relative humidity of 80% and temperatures ranging between 25 °C and 35 °C the absorption coefficient in the 500 Hz band = 0.3. Thus, the Delta M correction of (- 0.7)H_T/305 equals -0.5 dB for all 6 test cases. The height correction of Delta 1 = 20 log (H_T/H_R) must be individually computed as shown in TABLE 7. Referring to Section 2.6.7 it is evident that for helical blade tip Mach numbers above 0.800 the deviations are always greater than permitted; also, the test Mach numbers are all lower than the reference Mach numbers. Hence, a Mach number correction is mandatory.

Thus, in the end, an atmospheric correction Delta M, a height correction Delta 1, a Mach-number correction Delta 2 and (not included in the example) an ambient pressure correction Delta 3 must be added to the measured levels to obtain the fully corrected noise levels. Again, the 6 valid levels are arithmetically averaged, to provide the aircraft-specific certification level. In the example shown, using the minimum required 6 data points (ª valid test flights), the aircraft would have a noise certification level of 80.3 dB(A) with a 90% confidence level of 1.47 dB; this confidence level just barely suffices.

In the above illustration, a factor K = 150 for the Mach-number correction was again used. It will be recalled that ANNEX also allows to establish this factor through dedicated flight tests. The following example, reported by CAA |21| illustrates the procedure: within the framework of a Chapter-6 noise certification test measurements had been made at the relatively low ambient temperature of 8 °C (<u>Fig. 3.49</u>) open triangles), corresponding to a helical blade tip Mach number of 0.87. The reference temperature, however is 25 °C, with an associated reference Mach number of 0.84. To derive a noise sensitivity curve (in this case $L_{pA,max}$ vs helical blade tip Mach number), the propeller rotational speed was reduced in steps down to a helical blade tip Mach number well below 0.84 (as shown in Fig. 3.49, dark triangles). The noise sensitivity curve permitted the correction of the measured noise levels to those at reference Mach number. Since the actual Mach number was rather high, the correction amounts to some 8 dB, (which is actually larger than permitted). Still, in the case at hand, it was possible to repeat the measurements at the higher test temperature of 20 °C at some later time.

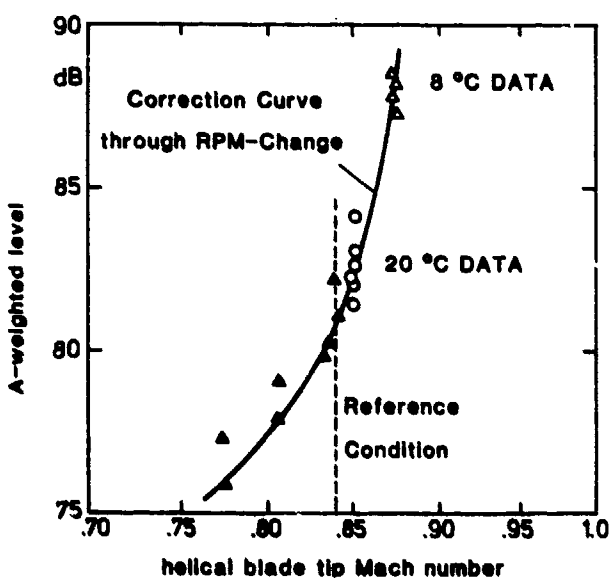


Fig. 3.49 Mach number (or temperature, respectively) correction through "in the field method" by means of repeated flights at different propeller RPMs (from Ref. 21)

Fig. 3.49 shows that these data points (open circles) agree very well with the original sensitivity-curve, thus lending credibility to the correction procedure. In the example shown here, the factor K would have a value of approximately 220.

3.6.2 Data Analysis - Determination of the Certification 'Effective Perceived Noise Level'

In order to determine a (final) Effective Perceived Noise Level, the procedure outlined in APPENDIX A to this AGARDograph should be followed. In the following, the procedure will be illustrated by means of specific data examples, pertaining to helicopter noise tests |22; 23|. It should be recalled that the noise certification of a helicopter is particularly complex, since measurements must be made simultaneously using three microphones, oriented at right angle to the flight path. Thus, each microphone position requires its own distance-correction for the point in time, when PNLTM occurs; this point in time must not necessarily be the same at all microphones. For the lateral microphones this also involves a fairly complex computation of slant angles. The average EPNL-values obtained at each of the three microphones (after individual correction) will yield the final EPNL, and this for each of the three procedures 'take-off', 'level flyover' and 'landing approach'. As a reminder: for heavy propeller-driven aeroplanes and for subsonic jet-aircraft only one maximum sideline level and one flyover level is required for a take-off test, and only one flyover level for the approach test, rather than 3.

Though the final certification noise level will be the EPNL, it is advisable to check the data first in terms of A-weighted flyover time histories. Disturbances in the noise levels are readily evident from a visual inspection of A-level time history traces. An example of such traces appears in Fig. 3.50, where for the 3 microphone-positions, i.e. 'sideline left' (in the flight direction), 'centerline center', and 'sideline right' the $L_{pA,slow}$-traces are shown. For certification, six such figures will be required. It is of course not surprising that the 3 microphones exhibit rather different traces for the same test flight. These differences are due to (1) the difference in the distances

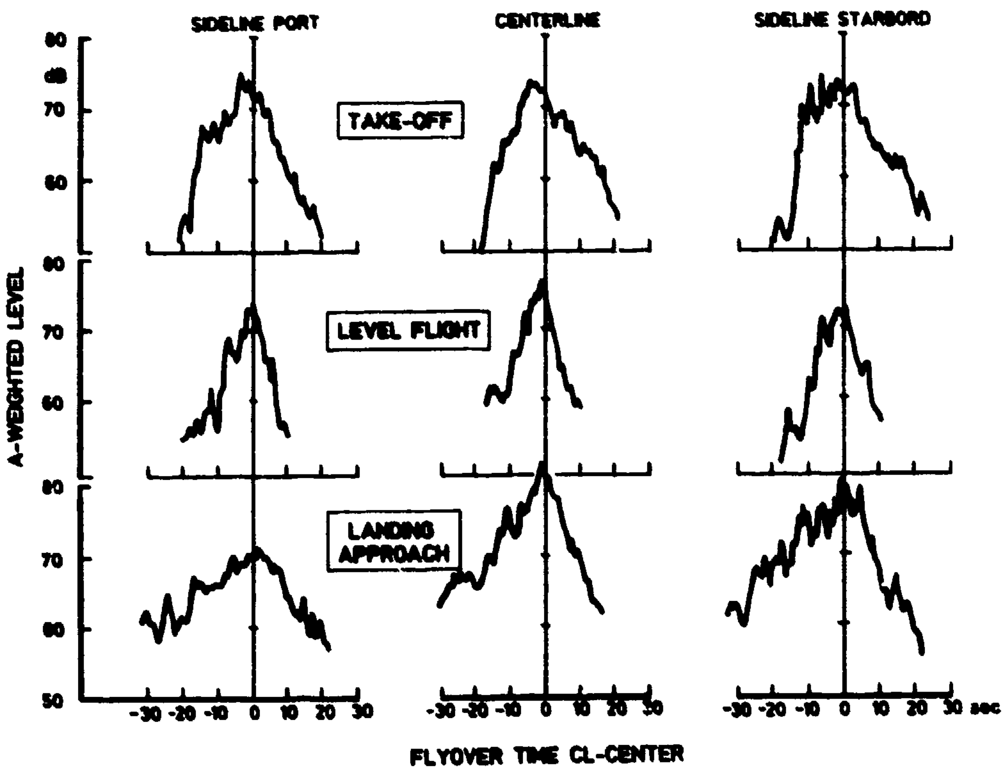


Fig. 3.50 Typical helicopter flyover A-weighted noise level time histories at 3 microphone locations 'sideline port', centerline center' and 'sideline starbord' for certification procedures 'take-off', level flyover' and 'landing approach'

to the aircraft, and (2) the differences in noise directivity, which are known to be rather pronounced for a helicopter and very dependent on the flight operational condition (e.g. the presence of a highly directional blade slap condition). It will be recalled that different noise sources dominate during a typical helicopter flyover: for an approaching helicopter one might first hear the (forward directed) main rotor high-speed impulsive noise, followed by main rotor rotation noise, then engine noise in addition to tail rotor contributions, and for the retreating helicopter again some impulsive type main rotor signals. Since each of these sources has its own speed dependence and directivity characteristics, the flyover signature fluctuates much more than that of a propeller-driven aeroplane (for an example see Fig. 3.47).

All traces shown in Fig. 3.50 are referenced to the instant in time (≙ 0 second) at which the helicopter was dirctly above the center microphone. The maximum noise levels of the microphones will usually not occur at that time.

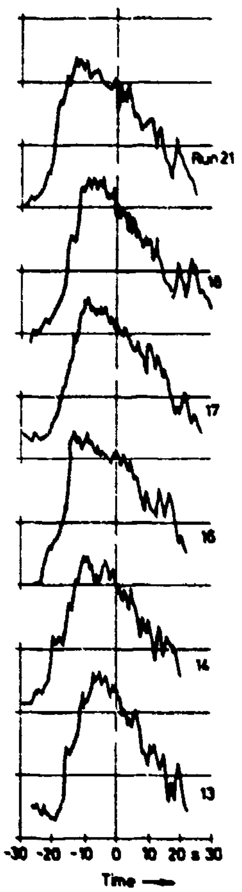


Fig. 3.51 Typical helicopter A-weighted noise level time histories at microphone location 'centerline center' for 6 nominally identical ('take-off') flyovers

Inspection of <u>successive</u> flyover A-level traces made under nominally identical conditions, as shown in <u>Fig. 3.51</u> for 6 level flyovers allows a judgement on the repeatability of the test. The similarity or dissimilarity in the A-level traces for repeated test flights are indications of the steadiness of the flight path (as affected by wind and atmospheric turbulence), the ability of the test pilot to reproduce the operational conditions for each successive flight, and the sensitivity of sound generation and radiation mechanisms to slight operational or atmospheric variations from test to test, etc. More importantly, from such initial level traces, one can select the time span which must be analysed to ensure the 10-dB-down-points required for the PNLT-computation. Since A-weighting differs from the noy-weighting, one cannot simply take the A-level 10-dB-down time spans as available from the A-level time histories. A time span should be selected which comprises approximately 15 dB below $L_{pA,max}$ before and after the occurrence of $L_{pA,max}$. A typical time span for a helicopter noise test can range from 15 to 30 seconds, thus yielding between 30 and 60 individual 1/3-octave band spectra.

The first step in the subsequent iterative processing of the data then involves the reduction of the recorded sound signal into 1/3 octave band spectra in a frequency range from 50 Hz to 10.000 Hz, i.e. in the 1/3-octave frequency bands from No. 1 (≙ 50 Hz) to No. 24 (≙ 10,000 Hz). This data is usually digitised and stored at 1/2 second intervals on a digital magnetic tape for further processing. For the analysis, Annex 16 recommends exponential averaging with a time constant of 1000 ms.

Each of these sequentially measured "raw" 1/3-octave band spectra must then be adjusted for

- o microphone frequency response
- o wind-ball effects
- o recording system frequency response

The microphone frequency response is available from response calibration supplied by the manufacturer or from a frequency response check of the microphone made prior to the test (note that microphones slightly change their frequency response in the course of several years, especially at higher frequencies).

The frequency-dependent insertion loss of a wind ball can be taken from data supplied by the manufacturer.

Adjustments for recording system response will be made on the basis of previous recordings of 'pink noise' (constant energy per 1/3-octave band), whereby an additional individual correction for the pin' noise generator's output may be necessary. A typical compilation of such spectral corrections is shown in Fig. 3.52, listed for band numbers 1 through 24. They account for the frequency responses of (a) all the wind-balls, (b) each of the microphones (microphone numbers 1, 2, and 3), (c) the (one) pink-noise generator used and (d) each of 6 data channels. According to the sign, these corrections will be added to or subtracted from each frequency band level.

CENTER FREQU.	WIND-BALL	MIKE1 Left	MIKE2 Center	MIKE3 right	PINK N. GEN.	PINK NOISE CALIBRATION FOR TAPE NO. 1	2	3	4	5	6
50	0.0	0.0	-0.3	0.0	-0.4	0.4	0.0	0.2	0.1	-0.2	0.3
63	0.0	0.0	-0.3	0.0	-0.4	1.4	1.1	0.3	1.1	1.0	1.0
80	0.0	0.0	0.0	0.0	-0.4	-0.2	-0.6	-1.2	-1.1	-0.6	-0.5
100	0.0	0.0	0.0	0.0	-0.2	-0.3	-0.5	-0.7	-0.4	-0.5	-0.9
125	0.0	0.0	0.0	0.0	-0.2	0.5	0.4	0.4	-0.1	-0.1	-0.2
160	0.0	0.0	0.0	0.0	-0.1	0.5	-0.3	-0.7	-0.4	-0.4	-0.6
200	0.0	0.0	0.0	0.0	0.2	-0.0	-0.4	-0.3	-0.1	-0.2	-0.4
250	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
315	0.0	0.0	0.0	0.0	0.0	-0.0	-0.3	-0.5	-0.3	-0.4	-0.5
400	0.0	0.0	0.0	0.0	0.1	-0.1	-0.2	-0.5	-0.2	-0.3	-0.3
500	-0.1	0.0	-0.2	0.0	0.0	0.1	0.2	0.0	0.1	-0.2	-0.3
630	-0.1	0.0	-0.2	0.0	0.1	-0.1	-0.4	-0.5	-0.2	-0.4	-0.6
800	[illegible]	0.0	-0.2	0.0	0.2	0.0	-0.3	-0.4	-0.2	-0.4	-0.6
1000	-0.2	0.0	-0.2	0.0	0.2	0.2	-0.1	-0.2	0.1	-0.1	-0.4
1250	[illegible]	0.0	-0.2	0.0	0.4	-0.2	-0.5	-0.5	-0.3	-0.5	-0.7
1600	-0.5	-0.1	-0.2	0.0	0.4	-0.4	-0.7	-0.8	-0.4	-0.6	-0.8
2000	-0.6	-0.2	-0.2	0.0	0.4	-0.4	-0.7	-0.8	-0.3	-0.6	-0.8
2500	-0.7	-0.3	-0.2	0.0	0.3	-0.9	-1.2	-1.3	-0.5	-1.0	-1.2
3150	-0.8	-0.3	-0.2	0.0	0.3	-1.1	-1.3	-1.2	-0.4	-1.1	-1.3
4000	-0.1	-0.4	-0.2	0.0	0.1	-0.8	-1.0	-0.7	0.2	-0.7	-0.9
5000	0.5	-0.6	-0.3	-0.1	0.0	-1.1	-1.3	-0.6	0.4	-0.8	-0.9
6300	0.6	-0.8	-0.6	-0.3	0.2	-1.1	-1.3	-0.1	1.1	-0.4	-0.6
8000	0.3	-0.8	-0.1	-0.3	0.5	-0.9	-1.1	0.7	2.2	0.1	-0.0
10000	1.0	-1.0	-1.0	-0.9	0.8	-1.4	-1.6	1.0	2.7	-0.0	-0.3

Fig. 3.52 Spectral corrections (in dB) of the data recording/reduction system

At this point then, the instrumentation-related response-corrected 1/3-octave band spectra at 1/2-second intervals during the flyover are available for each of the microphones. One such corrected spectrum might look as shown in Fig. 3.53. Even in this relatively coarse resolution, one distinguishes a rotational fundamental of the rotor around 50 Hz and several harmonics in the 100 Hz, 200 Hz, and 315 Hz bands. They imply the presence of pronounced "tones" which may affect the PNLT-computation. If the time span for the flyover (within a 15-dB-below-maximum A-level range) is 30 seconds, one would obtain 60 1/3-octave band spectra at each of the 3 microphones, i.e. a total of some 180 spectra.

The aircraft position at the time of the maximum tone-corrected Perceived Noise Level, 'PNLTM', must be known for applying the atmospheric and the distance correction, in addition to the duration correction which also depends on the ground speed. As a first step the "measured EPNL" is determined, i.e. the EPNL without yet applying any duration adjustment or atmospheric-absorption adjustment.

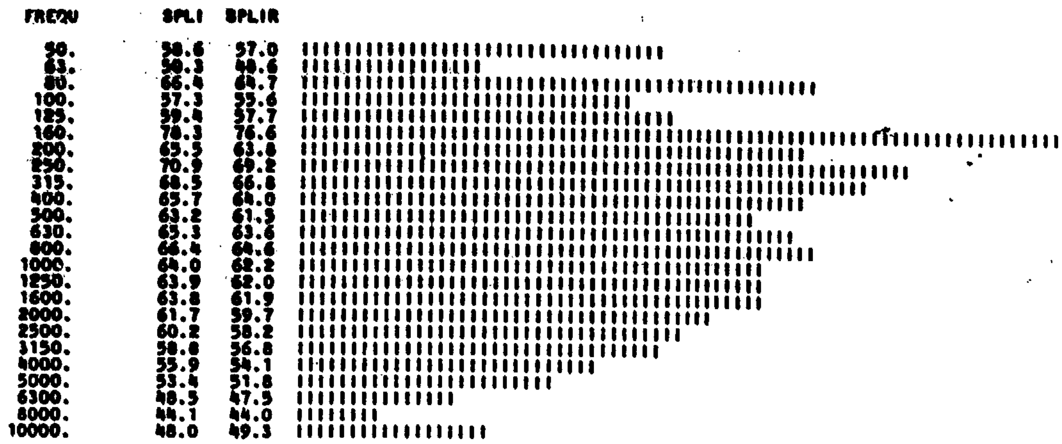


Fig. 3.53 Typical flyover 1/3-octave band spectrum

As outlined in Appendix A to this AGARDograph, this involves applying the noy-weighting to the 1/3-octave band spectra, the weighted summing of the perceived noisiness 'PN' in each of the 1/3-octave band spectra in order to arrive at the "Total Perveived Noisiness 'N'", to be further converted into the Perceived Noise Level 'PNL'. Thus, each 1/3-octave band spectrum is converted into <u>one</u> PNL-value.

Next, one must apply the tone correction. Application of the tone correction yields the <u>tone</u>-corrected Perceived Noise Level 'PNLT'. By means of this procedure, one obtains <u>one</u> PNLT-value only for each of the time-sequential 1/3-octave band spectra. One may now plot a PNLT- time-history such as in <u>Fig. 3.54</u>. This time history clearly has a maximum PNLTM at one point in time and 2 further points prior and after that maximum, which lie 10 dB below that maximum.

By means of this procedure we have now determined the instant in time and the position of the

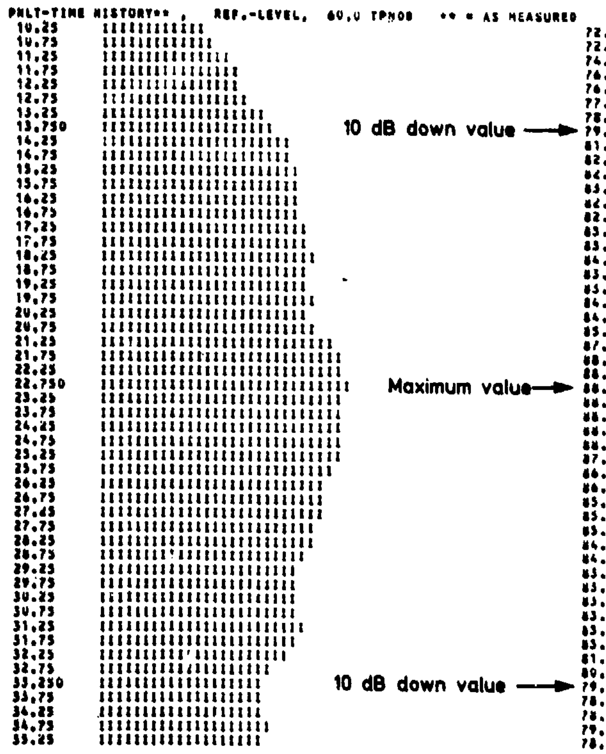


Fig. 3.54 Typical PNLT-time history for take-off flyover (each of these 51 data-points corresponds to just one evaluated 1/3-octave band spectrum, as shown in Fig. 3.53)

aircraft with respect to the microphone, at which the sound signal left the aircraft to produce, a short time later, the maximum PNLT on the ground; more importantly, we have determined the sound radiation angle between the aircraft and the receiving microphone. As will be recalled from Section 2.4.7 above, this angle is considered "aircraft specific" and independent of its flight trajectory position or of its climb- or descent-angle.

The next step pertains to correcting the flight trajectory to the reference trajectory. The actual flight path had been determined by some aircraft independent means, as discussed in Section 3.3.1. A typical trajectory plot (as obtained, incidentally, by means of kinetheodolite tracking) for a helicopter take-off is shown in Fig. 3.55. Clearly the helicopter deviated both laterally and vertically from the reference trajectory. It is particularly important in this example that the climb angle deviates from the reference climb angle.

It is now a straight-forward matter to derive from the known angle Θ that point on the reference trajectory, where the aircraft has radiated sound at that "specific angle" towards the ground microphone to produce PNLTM (see Fig. 2.12). From those points on the measured and on the reference trajectory one may now determine the slant distances QK and $Q_r K_r$, which are used in the correction procedure. As had been discussed in Section 2.7.7 of this AGARDograph, three particular correction parameters, Delta 1, Delta 2, and Delta 3, must be determined individually for each of the (also three) microphone positions.

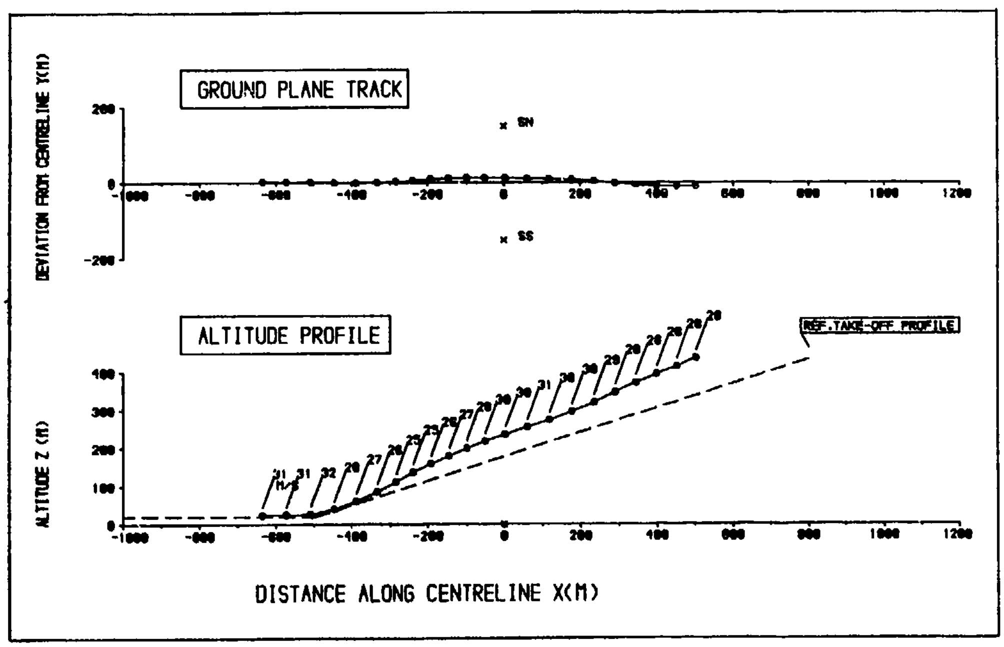


Fig. 3.55 KTH-determined helicopter take-off flight trajectory in the ground-plane and the height-plane in relation to the reference profiles

As a reminder: the Delta-1-correction accounts for (a) the atmospheric attenuation due the difference in temperature and humidity from reference, (b) the atmospheric attenuation due to the difference in slant range and (c) the (inverse square) distance attenuation due to the difference in slant range. A numerical example had been given in Section 2.4.7 of this AGARDograph on the computation of a Delta 1 correction. Delta 1 = $PNLT_{ref}$ - $PNLTM_{meas}$ is to be added to the measured EPNL-value. Let us arbitrarily assume a value of Delta 1 = 2.1 dB.

To derive the second correction term, Delta 2, it should be recalled that the 10-dB-down-time is both a function of distance and ground velocity. Therefore, an adjustment to the duration correction is required, when reference and measurement distances and ground velocities (= the flight velocity relative to the ground), respectively, differ. This additional correction, which must also be added to the originally measured EPNL-value, is

$$\text{Delta } 2 = -10 \log (QK/Q_r K_r) + 10 \log (V/V_r) \ *$$

If the relevant flight-speed V (in the case illustrated this would be a best-rate of climb-speed V_y) is 190 km/h vs. a reference speed of 200 km/h, Delta 2 would come out as -0.7 dB.

If we take the PNLT-time history plot shown in Fig. 3.54 as the pertinent example, we would read PNLTM as 88.8 dB at time 22.75 s, and the 10-dB-down-points as 79.7 dB at time 13.75 s and 79.5 dB at time 33.25 s. From these, one determines $EPNL_{meas.}$ as 90.3 dB. To this value, the corrections Delta 1 and Delta 2 must be applied:

$$\begin{aligned} EPNL_{corr.} &= EPNL_{meas.} + \text{Delta } 1 + \text{Delta } 2 \\ &= 90.3 \text{ dB} + 2.1 \text{ dB} - 0.7 \text{ dB} \\ &= 91.7 \text{ dB.} \end{aligned}$$

This corrected EPNL-value pertains to one microphone location and to one particular flyover. By means of a similar procedure, the EPNL-values at the remaining 2 microphones is determined. Each flyover is characterized by the arithmetic average of these 3 EPNL-values. Such average EPNL-values must now be determined for a minimum of 6 valid test flights. A typical printout for such a test is shown in Fig. 3.56, where there are columns for $EPNL_{corr.}$ in dB, $L_{pA,max}$ in dB, $PNLT_{max}$ in dB, C (= tone correction) in dB, D (= duration correction) in dB, Delta 1 correction in dB, Delta 2 correction in dB, and OASPL (= the overall unweighted maximum sound pressure level) in dB.

This information is provided for 6 test runs. The lower portion then shows the 3-microphone averages for each flyover, and - as the ultimate certification level - the average over the 6 test flights (88.8 EPNdB) and the standard deviation and the 90%-confidence level.

This final EPNL-value is then the specific noise certification level of the helicopter for one of the three test-procedures, in this case the 'take-off' test. This level must then be assessed against the noise limit (see Fig. 2.24).

This entire effort must now to be repeated for the 'level flyover' test, and for the 'landing approach' test.

For the level flyover procedure, however, an additional correction term, corresponding to a source noise correction Delta 3 must be determined, if any combination of the following 3 factors

- airspeed deviation from reference
- rotor speed deviation from reference
- temperature deviation from reference

results in a noise correlating parameter whose value deviates from the reference value of this parameter. Now, in the case of a helicopter in level flyover, this parameter would be the main rotor advancing blade tip Mach-number M_{adv}, being a function of true airspeed, rotor speed and outside ambient temperature. Suppose that the advancing blade tip Mach-number at reference con-

* for application to helicopter noise certification ICAO-CAEP intends to change this term into Delta 2 = - 7.5 log $(QK/Q_r K_r)$ + 10 log (V/V_r). The reader should consult the latest relevant addition to the ANNEX, as issued by ICAO.

RUN-NO.	EPNL (EPNdB)	LA(M) (dB(A))	PNLT(M) (TPNdB)	C (dB)	DUK(P) (sec)	D (dB)	Delta 1 (EPNdB)	Delta 2 (EPNdB)	OASPL (dB)
				SIDELINE NORTH 150 M					
13	90.3	75.3	88.8	2.5	19.5	-0.5	2.1	-0.1	82.7
14	86.7	70.1	83.4	1.6	23.0	0.4	3.5	-0.7	78.3
16	90.9	74.2	87.7	2.1	20.5	0.2	3.9	-0.9	82.7
17	86.4	69.8	82.8	2.2	27.0	0.6	3.7	-0.7	77.4
18	87.7	71.6	85.7	2.5	30.0	-0.6	3.1	-0.6	80.5
21	85.4	66.9	81.3	2.2	26.0	1.0	4.1	-0.9	76.4
MEAN	87.9	71.3							79.7
				CENTERLINE CENTER					
13	89.2	74.2	87.0	1.7	30.5	0.1	2.4	-0.4	80.9
14	88.5	72.5	85.2	1.8	22.5	0.3	4.1	-1.2	79.3
16	90.0	71.8	84.7	1.4	25.0	1.3	5.5	-1.6	81.5
17	89.2	73.2	86.3	1.7	23.0	0.3	3.7	-1.1	80.3
18	88.7	73.2	86.8	1.8	19.5	-0.5	3.3	-0.9	80.9
21	88.7	71.5	84.3	2.0	25.5	0.9	5.0	-1.6	78.8
MEAN	89.0	72.7							80.4
				SIDELINE SOUTH 150 M					
13	89.3	73.6	86.7	1.1	27.0	0.3	2.7	-0.3	81.0
14	89.2	71.9	84.4	1.0	27.5	1.4	4.3	-0.9	78.7
16	90.0	71.3	84.1	1.2	35.0	2.0	5.0	-1.2	78.2
17	90.0	73.6	86.8	1.4	26.5	0.4	3.5	-0.8	81.0
18	88.5	72.8	85.7	2.2	25.5	-0.0	3.5	-0.6	78.9
21	89.3	70.0	84.5	2.1	29.5	1.0	5.1	-1.3	77.9
MEAN	89.4	72.2							79.3
				AVERAGE OVER ALL THREE MICROPHONES					
13	89.6	74.4							81.5
14	88.1	71.5							78.9
16	90.3	72.4							80.8
17	88.5	72.2							79.6
18	88.3	72.5							80.1
21	87.8	69.5							77.7
MEAN	88.9	72.1			**FINAL RESULTS**				79.8
STD.DEV.	1.0	1.6							1.4
90% CONF.	0.8	1.3							1.1

Fig. 3.56 Summary of exemplatory noise measurement results for a helicopter take-off procedure

ditions had been determined as 0.860 and that - for whatever reason - measurements were conducted at a lower M_{adv}. Then one should obtain a "noise sensitivity curve" (dependence of PNLTM on M_{adv}) through additional dedicated flight tests.

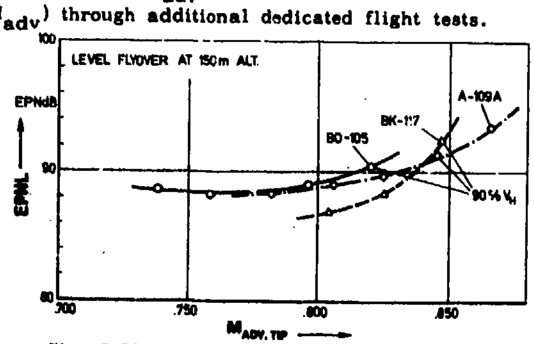


Fig. 3.57 Noise sensitivity curves for three medium weight helicopters

Fig. 3.57 illustrates the general problem on the example of noise sensitivity curves for a number of medium-weight helicopters. The rather pronounced sensitivity of EPNL on M_{adv} is quite obvious. Fig. 3.58 now shows an extreme case; here EPNL-values were available from approximately 0.805 up to 0.845, while the reference conditions called for an M_{adv} of 0.86. In this case it would be permitted to utilize the slope of the sensitivity-

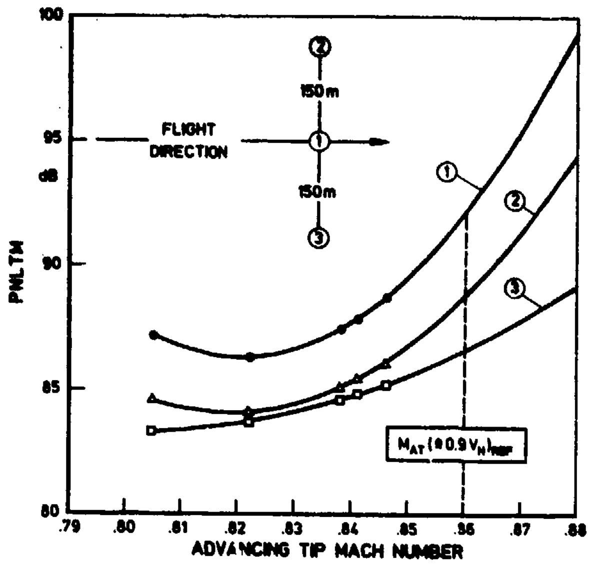


Fig. 3.58 Determination of noise sensitivity curve through dedicated flight tests for purposes of source noise correction

curve to extrapolate to the reference value. In the case shown this would involve an upward correction of approximately 3 dB, probably a rather excessive correction. In the end, the value of the Delta 3 source correction must be added to the measured EPNL-value in addition to Delta 1 and Delta 2.

This section on the determination of a noise certification EPNL-value used the helicopter noise certification as an example. The noise certification procedures for heavy propeller driven aeroplanes and for subsonic jet aeroplanes require similar evaluations to produce a corrected EPNL.

4. TEST ASPECTS AND ANALYSIS TECHNIQUES IN FLIGHT AND WIND TUNNEL NOISE RESEARCH

The noise measures L_{pA} and EPNL have been accepted for certification purposes. They are, however, much too coarse to provide much insight into the important aeroacoustic source mechanisms of the various noise generators on flight vehicles. Understanding the source mechanisms of aircraft related noise generators such as propellers, rotors, fans, jets etc. in their dependence on aircraft operational, geometric and atmospheric parameters is however paramount not only in making these sources quieter but also to enable improvements in the noise certification procedures themselves and to eventually allow for more stringent noise limits.

Noise testing and analysis techniques for the purpose of flight noise research differ - sometimes substantially - from those in the "well-established" noise certification procedures. In research there is often a need for an extended range of parameter-variations and for a much more detailed analysis. For example, narrow-bandwidth analyses in the frequency-domain and analyses in narrow time-increments in the time-domain are called for.

In aircraft noise research both flight and wind tunnel tests are conducted. In planning and executing such tests, there is a need to understand their particular advantages or disadvantages. To illustrate special techniques involved, the following sections will discuss some testing and analysis aspects in conducting aeroacoustic research. Six specific areas will be treated:

- Flight (and Ground) Noise Testing of Subsonic Jet-Aeroplanes
- Flight Noise Testing of Propeller-Aeroplanes
- Flight Noise Testing of Helicopters
- Jet Noise Testing in Wind Tunnels
- Propeller Noise Testing in Wind Tunnels
- Rotor Noise Testing in Wind Tunnels

The intent of this AGARDograph-Chapter is however not to provide a fully comprehensive discussion of all possible test and analysis procedures that may occur in the course of aircraft noise research in the widest sense. Rather, selected test and analysis techniques are introduced and exemplified through a discussion of several recent aeroacoustic research projects. From that the reader should obtain a "gut feeling" for the variety of experimental aspects in aircraft noise research as opposed to those pertaining specifically to noise certification.

While the material in the previous Chapters 2 and 3 is in principle sufficient to plan and conduct noise certification work, the account in Chapter 4 is a sequence of carefully selected acoustic research experiments, which is no more than a brief introduction to the vast and complex subject of aeroacoustics. Work on such topics as 'identification of noise sources' or 'reduction of acoustic signatures', certainly requires the collaboration of a specialist. In order to moderate the optimism which might result from the rather successful acoustic experiments described, some of the less obvious effects which may occur in aeroacoustics are noted in passing and render this such a challenging subject.

4.1 Flight Testing vs Wind Tunnel Testing

When studying aircraft related acoustic source mechanisms, it is generally advantageous to "break down" the noise as emitted by the aircraft into its various constituents. For a propeller-driven aeroplane these will be the propeller(s), the engine(s), gear boxes, and the engine exhaust. For other types of aircraft airframe noise (e.g. from wheel-wells, landing gears, flaps, slats, etc.) may also require special attention. Such airframe noise can be a problem especially during the landing approach phase of subsonic commercial jet aircraft. For a helicopter the main rotor, the tail rotor, the engine(s) and the transmission produce significant noise components.

Though each of these noise contributors acts as an individual source, some also interact: for example, the propeller flow field and its noise-generation are affected by the engine-cowling, the wings and - in a pusher-configuration - also by upstream struts and tail-components. The particular installation of a jet-engine or of a propeller may also influence the way it radiates sound. A wing or fuselage may act as a reflector and redirect or even emphasize the sound. The tail-rotor of a conventional helicopter operates in the highly unsteady wake of the main rotor or in its trailing vortices or in the wake shed by the main rotor hub. Thus, the interaction per se of individual noise-contributors is an important additional source of aircraft noise, requiring particular attention.

Flight testing the actual aircraft in its natural environment gives the most realistic information. The aircraft operates the way it is intended to, and there are no scaling problems. These advantages must, however, be assessed against limited variability of the test-parameters and the statistical uncertainties of repeated measurements. Also, acoustic signals from a flying object are affected by Doppler-shifts and the sound passes through an inhomogeneous and turbulent atmosphere before arriving at a ground-microphone. These latter are often positioned some distance (e.g. 1.2 m) above the ground, which can cause critical ground-reflections. Furthermore, the aircraft must be tracked rather precisely to allow unequivocal synchronisation of sound signature and aircraft position. Hence, data acquisition, reduction and eventual interpretation are affected by a number of non-source-related influences, which often result in severe data scatter.

Many of these problems are avoided in wind tunnel testing, especially, if high quality open test section tunnels with low noise are available. Wind tunnels allow essentially indefinite test-time under usually very stable and reproducible conditions, since the environment can be fully controlled. Also source and receiver are in a fixed relative position, which facilitates source identification. Wind tunnels permit the testing of components (propellers, rotors, fans, jets) by themselves or in appropriate combinations and off-design operation can be safely executed.

These advantages are counteracted by the sometimes excessive aerodynamic background noise and tunnel flow turbulence, and by the proximity to the model of a shear layer, introducing extraneous sounds. In such "open-jet" wind tunnels it is often necessary to measure outside the jet-flow in the surrounding test-hall; in that case sound propagates through the free shear layer, which can distort the acoustic signal along its way to the measuring microphone. This shear layer is usually irregular in shape, and it also entrains turbulence; the propagation of sound through such an irregular and turbulent shear layer can change its directivity and spectrum. Moreover, the turbulence and vorticity in the shear layer can act as sources of sound. One cannot readily infer, therefore, from the sound received outside the jet, which are the sources inside the jet: some of the sound might not come from the interior of the jet at all, and that which was generated in the jet could have been emitted with a distinctly different spectrum and directivity.

Appropriate (subsonic) wind tunnels for aeroacoustic testing must therefore fulfill a number of requirements: They must foremost possess the aerodynamic features of high quality conventionel tunnels, such as good flow quality (straight velocity-profiles and low turbulence). For aeroacoustic testing only wind tunnels with an open test section can be used. The open test section must be surrounded by a large anechoic test hall to provide the necessary free-field conditions. The wind tunnel drive system (fan) should generate as little noise as possible and - as an additional measure - the duct walls and the guide vanes should be treated with absorbtive material.

In an open test section tunnel, the "lower"-frequency-limit of the absorptive treatment on the surrounding test hall walls may in effect be rather high. Such walls may in cases more reflect than absorb the impinging sound. In wind tunnel testing, it will be often necessary to employ scale models. In that case one is faced with Reynolds-number problems, which can adversely affect both the aerodynamics and the acoustics of a test.

Another important feature is wind tunnel size. In the "best of all worlds" it would be possible to determine the sound-field around an aeroacoustic noise generator still within the potential core of the tunnel free-jet but in the geometric/acoustic far-field (the latter requirement is related to the physical size of the model and to the wavelength of the sound considered). In such a case sound propagation through the shear-layer is avoided. This requirement calls for test cross-sections many times larger than the model to be tested.

There are a number of highly qualified tunnels that fulfill all or most of the above requirements. Examples are the German Dutch Wind Tunnel (DNW) in the Netherlands (Fig. 4.1a), the CEPRA 19 Wind Tunnel (Fig. 4.1b) at Saclay near Paris, and the Boeing Large Anechoic Test Chamber (Fig. 4.1c) in Seattle. The DNW combines all aerodynamic and acoustic features in an optimum way, and many experts believe that it is the best facility for aeroacoustic research available at present.

Aircraft noise research cannot rely on one type of experimentation only. Often a combination of full-scale ground and flight testing, and full-scale and model-scale wind tunnel testing is necessary to obtain all desired information.

4.2 Flight and Ground Noise Testing of Subsonic Jet Aeroplanes

Noise certification of subsonic jet aeroplanes requires a minimum number of 6 valid flights for each of the two test procedures 'Take-off' and 'Approach'. Since both flyover and sideline noise data are to be obtained within the take-off flight, in principle only 12 flights are necessary. The actual acquisition of noise certification data of a Chapter 3 aircraft, for example, could thus be achieved within a relatively short time span.

In practice however, preparation, test-conductance and data reduction represents a substantial effort. Frequently, the validity of a test flyover can only be established some time "after the fact", when off-line analysis had been performed. In that case a new test series might become necessary.

Fig. 4.1a German Dutch Wind Tunnel (DNW) in the open test section configuration

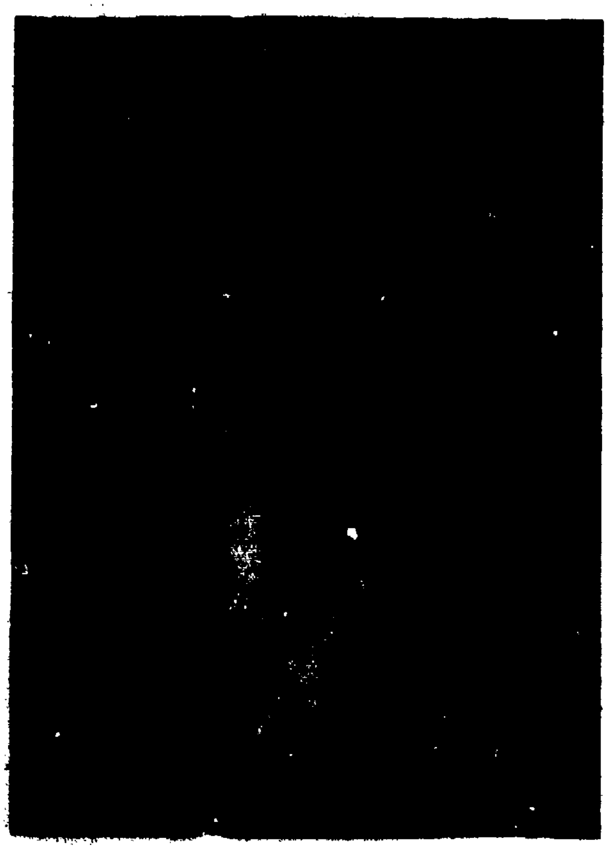


Fig. 4.1b

ONERA CEPRA-19 acoustic wind tunnel, a facility of CEPr (Centre d'Essais des Propulseur)

Fig. 4.1c Boeing Large Scale Anechoic Test Chamber

An airframe manufacturer, having to go through the noise certification procedure for a newly developed aeroplane would therefore attempt to obtain a broader acoustic data base on his "datum"-aircraft, expecting the eventual development of "derived versions". Prediction of the noise levels, and of noise certification levels in particular, for such a derived model could then to a large extent, or even entirely, be based on data from the original aircraft. Perhaps only a few check-flights would be necessary or flyover noise measurements could be eliminated altogether.

Derived versions differ physically from the original aeroplane in a number of respects: for example, there could be an increase in take-off weight or engine thrust, or there could be changes to the power plant. Also a derivative aircraft could be stretched or shrunk. Such measures are likely to affect the noise as generated and radiated by the aircraft, as well as the reference-speed and the distance between the reference measurement points and the aircraft. If enough information, say, on the effect of engine power setting, of airspeed or ground-speed, or of distance (slant distance, in particular) had been obtained on the original datum aircraft, many acoustic changes in the derived version could be accounted for analytically or by means of (moderate) data extrapolation. It is imperative, however, that the original data set is extensive enough for the purpose.

In the following some aspects of the acquisition of the necessary information will be discussed, and an approach be generically described how flyover noise may be predicted on the basis of full-scale static engine tests and model experiments of jet engine components.

4.8.1 "Noise/Power/Distance"-Curves

To acquire the necessary extensive acoustic data set, so-called 'noise/power/distance (NPD)' curves are to be generated over a wide range of parameter variations. If the data is to be used for predicting certification noise levels, then the relevant noise parameter is the EPNL. The corresponding engine "power" parameter would then be either the net thrust F_N for a low bypass turbo-fan engine, or the fan rotational speed N_1 for a high bypass fan-jet engine.

To generate such plots, a sufficient number of noise measurements must be made for different engine power settings, speeds and (slant) distances. Specifically, "flyover/side-line noise tests" with the aircraft in the take-off configuration could be conducted for 'take-off' engine power and 'cut-back' engine power, and several values in between. "Approach noise tests" with the aircraft in the landing configuration (landing gear deployed) could again be conducted with different engine power settings and flap-settings.

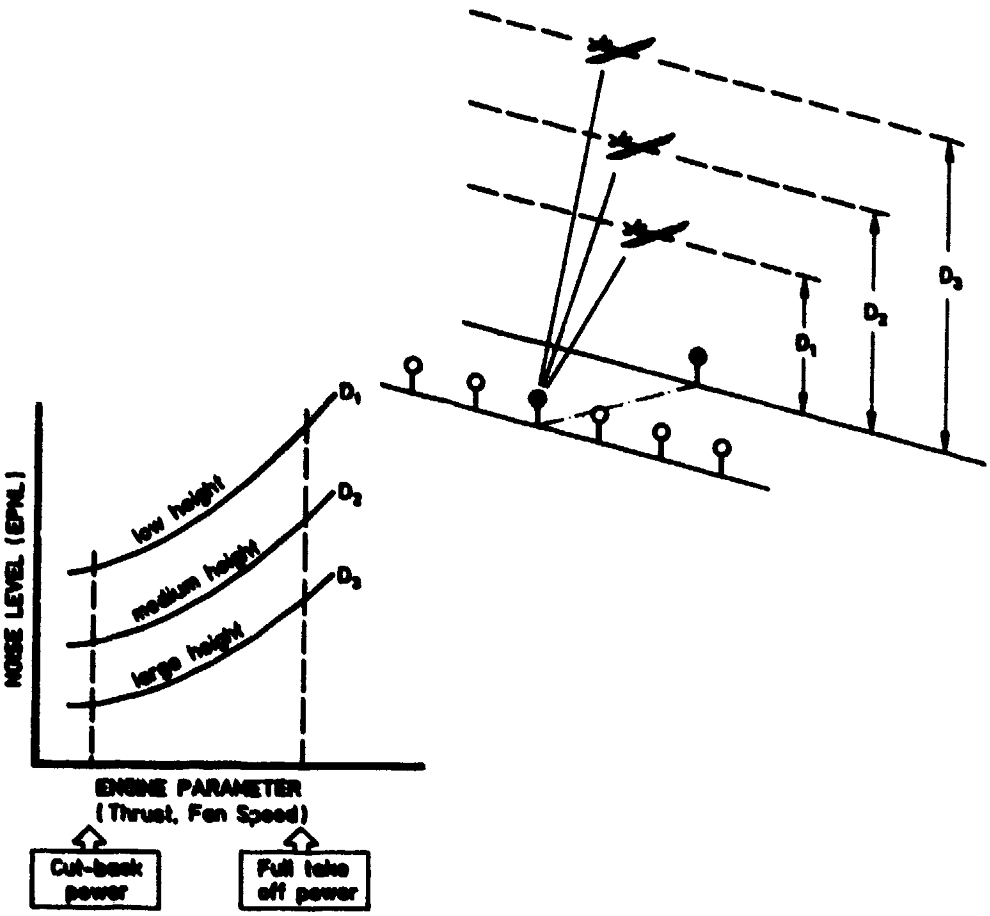


Fig. 4.2 Schematic of generalised noise data base acquisition for use in the noise certification of a "flight-datum-" and then for the "derived-version"- aircraft

Fig. 4.2 is an illustration of how data may be acquired and how the result might look like. Here EPNL is plotted for parameters thrust (or fan rotational speed, as the case may be) and distance for a fixed flight speed. Additional plots must then be obtained for a number of other flight speeds. Of course, all noise data must be corrected to the reference atmospheric conditions, following the procedures described in Section 2.2 of this AGARDograph.

4.3.3 Static to Flight Projection

As mentioned, a derived version may be equipped with a modified power plant, where some acoustically effective changes had been made to the original engine or a different (though broadly similar) engine by another manufacturer might have been installed on the same airframe. Flight testing for noise certification can then often be avoided through comparative ground-static tests of both the flight datum and the derivative power plants using static open air test facilities.

Here the philosophy is to first obtain acoustic data on the datum engine through a ground test. The same engine - installed on the aircraft - will then be noise tested under actual flight conditions; flight and aircraft installation effects on the engine noise will thus become apparent. It will be advantageous to consider individually - if possible - noise producing components of the engine (e.g. fan, compressor, turbine, jet-exhaust) and of the airframe and to determine how they (individually) are affected by the actual flight conditions.

It is now argued that the flight effects on a (broadly similar) derivative engine/aircraft configuration are quantitatively similar. Thus, using acoustic data as obtained by means of a ground based test of a derivative engine one could extrapolate towards the noise under flight conditions with considerable confidence.

The crucial aspect of such an approach is the attainable accuracy in projecting static noise data towards flight noise data for any particular given engine. An engine in flight operates under conditions of high-speed inflow; also the engine exhaust jet is aeroacoustically affected by the change in relative ambient speed, leading to a downwind spreading of the jet-sources.

Individual aspects of this approach will now be discussed.

(a) Engine Inflow

In static tests, the inflow into the engine must not be affected by ground effects. Any unsymmetry in the intake-flow will substantially distort the noise generated. In flight, such unsymmetry would not normally occur, certainly not under conditions of straight level flight. The "distorted-inflow problem" is minimized by employing large spherically shaped inflow screens (Fig. 4.3). The engine itself should be mounted sufficiently high above ground to ensure essentially undisturbed and radially symmetrical inflow.

(b) Installation Effects

In predicting the noise of the engine, as mounted on the aircraft, installation effects must be accounted for. Usually, engines are mounted close to the wings or the fuselage. Exhaust noise is particularly affected by reflections off nearby wing surfaces. Both the acoustic intensity and the noise directivity could be substantially changed.

If the datum-engine and the derived version engine are broadly similar, one could expect the influence of forward speed and engine airframe installation to be similar. Hence, a rather straight forward static-to-flight extrapolation for the "derived version engine" should be possible on the basis of the static-to-flight relationship of the datum engine.

(c) Data Analysis

Measuring the flyover noise of a jet aircraft equipped with modern high-bypass engines is inherently complicated. The speed of the aircraft relative to the ground is typically much higher than that of propeller-driven aeroplanes. If the flight height is low, in the order of a few hundred meters only, as would be the case during initial climb or final approach, the angular radiation angle changes rapidly.

Fig. 4.3 Spherical intake flow straightener

In measuring the noise from a high speed aircraft in overflight the inherent Doppler-effect causes a time-compression (during approach) and a time-expansion (during fly-away) of the signal in the time-domain due to the source motion; hence, the spectral information obtained is affected in a number of ways. This is especially true if narrow-band spectra are to be determined which are of interest in identifying certain tone-producing components (such as the fan or compressor- and turbine-stages). In analysing flyover noise signals for reasons of tonal component identification it is therefore necessary to "de-Doppler" the acoustic signature. An excellent description of the relevant technique is provided in |24|. This technique involves the calculation of the sequence of reception-times corresponding to a particular set of regularly spaced emission-times for an assumed source position and velocity. This way an emission time history is constructed from the received signal. If the microphone is sampled at these reception times, then the Doppler-effect is removed.

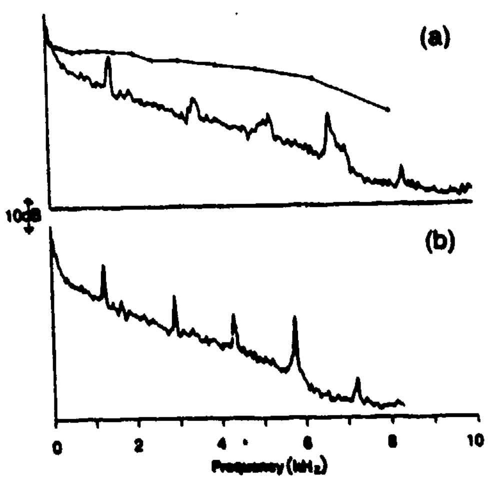


Fig. 4.4 De-Dopplerization of high-speed/low-altitude flyover jet-aircraft noise signature (from Ref. 24)

In spectral analysis, the accuracy after transforming a time-affected signal to the frequency domain depends on a trade-off between bandwidth and averaging time. In flyover noise tests, the averaging time duration is limited, since the emission angle changes rapidly. By using, however, a number of microphones spaced longitudinally under the flight path, one can effectively increase the averaging time without losing angular resolution. Fig. 4.4 (reproduced from Ref. 24) illustrates the dramatic improvement in frequency resolution after de-Dopplerisation. While in the original (Doppler-affected) signal the tones - although being clearly discernible - appear broadened and blurred, de-Dopplerisation now moves these tones to the correct frequency (where they can be related to known engine-associated rotational speeds) while at the same time making them appear much sharper and unblurred.

(d) Separation of Engine and Airframe Contributions

The noise signature of a jet-powered aeroplane contains contributions from the engines and the airframe. The engine noise itself combines fan, core (combustion and turbine), and jet contributions. Airframe noise, which tends to dominate at lower engine powers, such as during approach, is caused by the external airstream over structural components (flaps, landing gears, wheel wells, struts, stringers, etc.). The assessment of the contribution from airframe noise should always be an integral part of any flyover noise study. This may by obtained by conducting flyovers with engines at flight idle. The radiated noise would then essentially represent the aircraft's airframe noise.

Airframe noise increases approximately with the 5th power of a representative speed (a flight speed). One could thus obtain an order of magnitude estimate of the airframe noise at higher engine-powers and flight-speeds, respectively, where airframe noise could not any more be determined directly.

(e) Jet Noise/Core Noise

If the effect of flight on jet noise were just a translation at uniform velocity, then an overall Doppler shift and refraction of sound at the jet/atmosphere interface would be the only result. The reality is more complex, because even if one was only to compare an aircraft in steady flight with a static ground noise rig, the flow in the jet is non-uniform and unsteady. Thus the Doppler shifts depend on location and time within the jet, i.e., on the flow structure.

Sound propagation in a jet is affected by vortices, turbulence, shear layers, shock waves, and any other properties in the flow pattern. A Doppler shift varying in space and time is equivalent to a change in direction of propagation and frequency, i.e., all these flow effects change the directivity and spectrum of sound. Also, even if there was initially a coherent sound beam, with all waves in phase, propagation through the non-uniform or unsteady jet flow causes phase leads and lags, and hence distinct wave components can interfere.

There are successful examples of calculating flight effects on noise, but they involve a careful study of physical phenomena and sophisticated mathematical analysis. Simple formulas allowing the prediction of in-flight noise from static noise tests have given at best correct trends, because of the difficulty in taking into account all the effects mentioned above.

Prediction of the engine noise from static data should individually cover the fan, the core and the engine exhaust jet. In case of a modern high bypass engine, the engine exhaust itself consists of the hot core jet and the surrounding annular cold bypass jet. The (full-scale) flyover noise from the core and from the exhaust jet may, however, be predicted on the basis of model tests. Such an approach is described in |25|. Here, a 1/20-scaled coaxial hot/cold jet experimental set-up corresponding to a Rolls-Royce RB 211 engine was placed in the large NGTE anechoic chamber. The coannular nozzle was positioned within a circular flow nozzle of larger diameter, providing the forward flight simulation air stream. Measurements were taken with microphones placed at the correctly scaled farfield position for later comparison with the flyover distance. By means of this set-up the "uninstalled-engine" jet-noise could be determined. To account for the fact that the aircraft engine is mounted under the wing, an appropriately scaled wing was placed next to the model coaxial jet set-up. Core noise was determined on a static full-scale engine set-up, where by means of certain analysis-techniques, the jet and the core noise contributions could be separated. Next, a loudspeaker system was put upstream of the internal centerbody of the primary nozzle in the model set-up in the anechoic chamber. A broadband signal was played into the loudspeaker and the resulting noise was measured in the presence of a wing, but in the absence of flow. The resulting directivity pattern was then applied to the "uninstalled core-engine" noise spectrum, as measured within the full-scale engine experiments.

This information was finally used to derive the combined "installed jet" and "installed core" noise spectra at various angles around the engine exhaust orifice.

(f) Remark of Caution

Methods of extrapolating flight effects on noise applying to derivatives of an existing engine assume that:

- for the existing engine, both static and flight noise data are already available;
- the derivative engine has a similar configuration, and only static noise data is needed.

This way of extrapolation assumes that noise generation and shielding effects for the original and derivative engine are similar, which could be true if the mechanical configuration and operating condition are similar.

On the other hand, it would be very difficult to extrapolate from the noise of a turbojet to that of a turbofan, even if the core engine were the same, because: (i) the fan emits much more noise to the front of the engine, and its reduction requires special techniques; (ii) the noise of the jet core is reduced by refraction in the by-pass flow of the turbofan. Thus one might expect the turbofan to radiate more noise to the front and less to the rear than the comparable turbojet. A quantitative prediction of the effect or methods of noise reduction would require much detailed research.

4.3 Flight Noise Testing of Propeller-Aeroplanes

To investigate propeller noise characteristics by means of flight experiments, several approaches are possible:

(1) Mounting the microphone, or an array of microphones, on the aircraft itself. This provides a realistic environment for the tests and has the advantage of a fixed source/receiver configuration. Usually, only measurements close to the source are possible since the maximum attainable distance between the relative positions are determined by the aircraft's dimensions and its geometry.

(2) The use of a low-noise companion aeroplane which flies in formation with the test aircraft and can therefore maintain a fixed relative position of source and receiver. Such a companion aeroplane can carry one or more microphones. The advantage of this approach is the essentially complete freedom of the relative positioning of source and receiver: the companion aeroplane may fly under, above, to the side, ahead or behind the test aircraft. In this manner a complete survey of the propeller noise field all around the test-aircraft can be made. The required accurate station keeping, however, makes this test difficult to execute.

(3) Conventional flyover tests, where one or more stationary ground microphones measure the noise of the test-aircraft flying over the measurement station.

4.3.1 Quasi-stationary Tests by means of Aircraft-mounted Microphones

Nearfield noise measurements on propeller aircraft can best be done by mounting microphones directly on the aircraft. The microphones are often flush-mounted in the fuselage surface, a technique that can only be sensibly used for wing-mounted propellers (i.e. for twin- or multiple-engine aeroplanes). Alternatively, the microphone(s) can be mounted on a support structure (strut, boom) off the aircraft wing or nacelle.

(a) Types and Arrangements of In-flight Microphones

Microphones embedded in the fuselage surface are normally used to study problems related to interior noise. If positioned near to the propeller rotation plane, such microphones are exposed to the periodic impingement of the rotating, blade-associated, pressure field and to the nearfield acoustics of the propeller.

The DORNIER Company used fuselage-embedded 1/4-inch-diam condenser microphones on their "TNT-Experimental Aeroplane"; the microphones were mounted in the plane of rotation of the propeller and thus at the given distance from the propeller hub |26|. The microphone signals are however affected by the surface boundary layer noise and by structural vibration. These effects are not very significant as the microphones are very close to the source and the signal is strong.

Although used for noise studies on a commercial jet-liner (a B 747), rather than on a propeller-aeroplane, the approach taken by the Boeing Commercial Airplane Company is of interest in this context |27|. Here a fluctuating-pressure transducer was mounted in a special housing inside a rivet hole. This sensor had to be insensitive to weather and other environmental effects, small (approximately 1/10 " diam"), and capable of measuring surface-pressure levels or acoustic levels from as low as 85 dB up to 130 dB. While condenser microphones would be the preferred choice for this purpose, they are rather sensitive to moisture and cannot be installed in advance of a flight test series and then be left exposed to the weather and mechanical hazards. Therefore a piezo-electric type was selected. On earlier occasions sensors had been bonded to the outside fuselage surface with leads taped to the skin and routed to the interior through a window blank. As these sensors protruded above the surface of the fuselage, they had a tendency to generate self-noise, thus defeating the purpose of low-noise measurements. The problem was solved by mounting an appropriate small-diameter pressure sensor in an available rivet-hole.

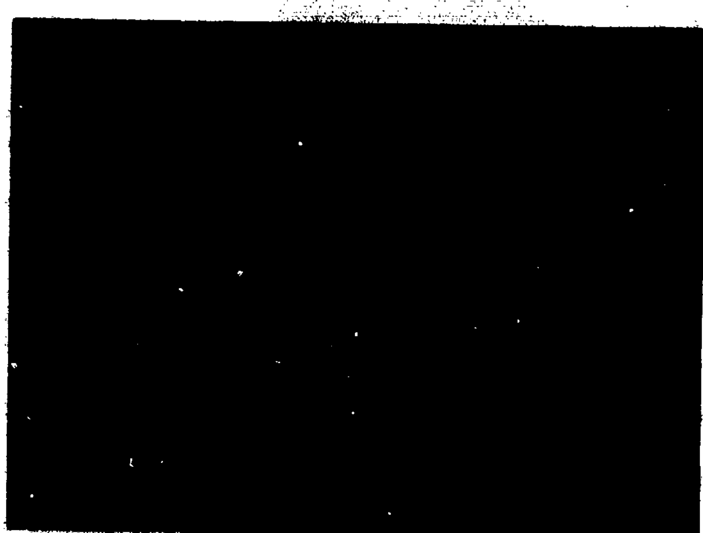


Fig. 4.5a Microphone nose boom array on Cessna aircraft

Microphone-carrying nose booms are also often used. Figs. 4.5a and b show two examples, one representing an array of microphones on a Cessna T207, the other on a Fairy Gannet, both for use in propeller noise studies.

In the context of a natural laminar-flow experiment on a B 757 test airplane, a microphone probe for measuring engine

Fig. 4.5b Microphone nose boom on Fairy Gannett aircraft

noise near the laminar-flow glove on the wing is described in |28|. Here the original condenser microphone of a commercially available 1/4-inch-diam nose-cone arrangement was replaced by a piezo-resistive sensor of the same diameter. In this way the low self-noise qualities of the nose cone arrangement with the sturdiness and the insensitivity to ambient influences of the piezo-resistive sensor were combined.

Self-noise studies of nose-cone equipped microphones using a 'Janus' sail plane are discussed in |29|. Here, an array of several parallel booms on the glider wing (Fig. 4.6) allowed a direct comparison of different nose-cone diameters under identical conditions. A dimensionless plot of 1/3-octave-band self-noise spectra for cones on 1/4"-, 1/2"-, and 1"-diameter booms showed that the latter was superior to the two others (Fig. 4.7).

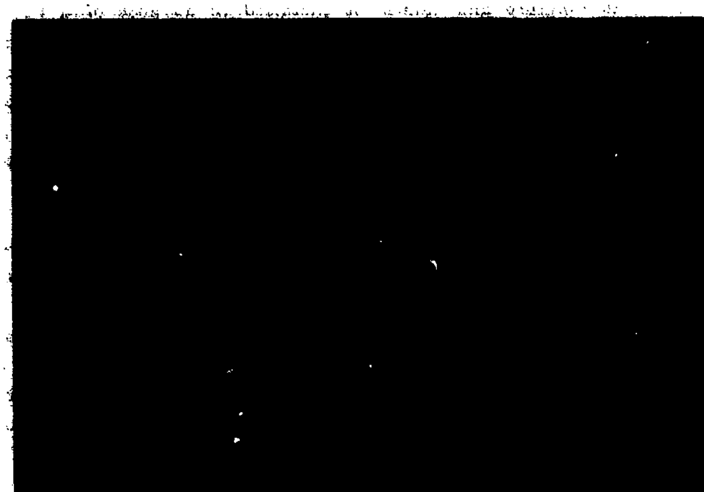


Fig. 4.6 Airborne test set-up to compare several microphone/nose-cone arrangements for self noise generation on a glider plane

(b) Propeller Noise Measurements

Nearfield Studies on Counter-rotating Propellers

The noise tests on the counter-rotating propellers (CRP) of the Fairy Gannet aircraft produced a rather intriguing experimental result: as both propellers could be operated independently, it was possible to drive them at slightly different rotational speeds. At equal RPMs and blade numbers,

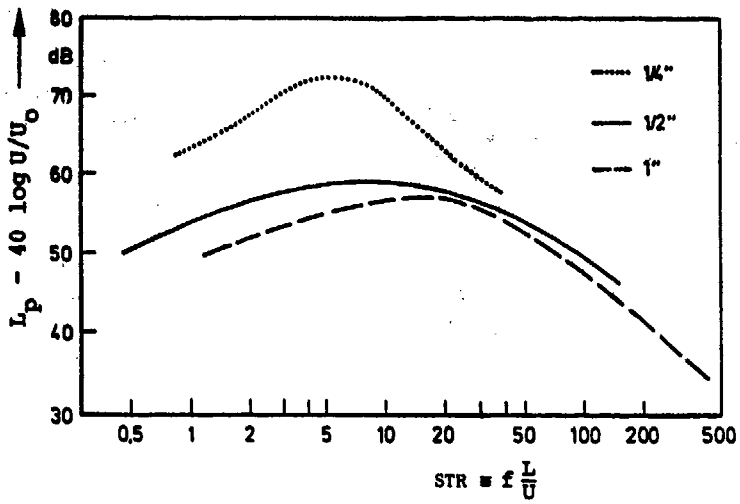


Fig. 4.7

Compari··n of normalized self-noise spectra of ogive nose-cone equipped condenser microphones of different diameters

both the steady and the unsteady source effects would produce noise components at the blade passing frequency of one rotor and its harmonics, and no new frequencies are introduced by the second propeller. Each propeller produces, however, its own set of fundamental and harmonic frequencies due to the steady sources (thickness and blade-loading), which can be readily identified on account of the slight difference in RPM (Fig. 4.8). The obvious peak in between, now, is due to unsteady aerodynamic interaction. These results are theoretically explained and physically described in |30 and 31|. The method provides a powerful diagnostic tool in CRP-noise research.

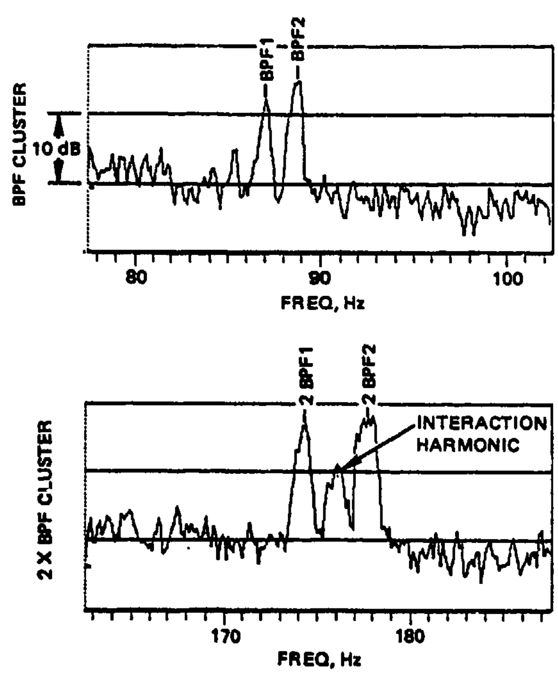


Fig. 4.8 Frequency splitting in the noise from a Hamilton Standard Gannet counter rotating propeller operating at slightly different RPMs (from Ref. 31)

Another interesting test result of this experiment is shown in Fig. 4.9, providing the azimuthal variation for the first four harmonics of the blade-passing frequency (BPF). This information was obtained by very slowly incrementing the mesh-point around the propeller circumference and recording harmonic sound pressure variations as function of time. Thus the pattern was moved past the "stationary" microphone boom. (This result illustrates the importance of considering different azimuthal locations in counter-rotating propeller-noise research, rather than only one azimuthal location, as would be sufficient in single propeller configurations at no angle of flow-incidence).

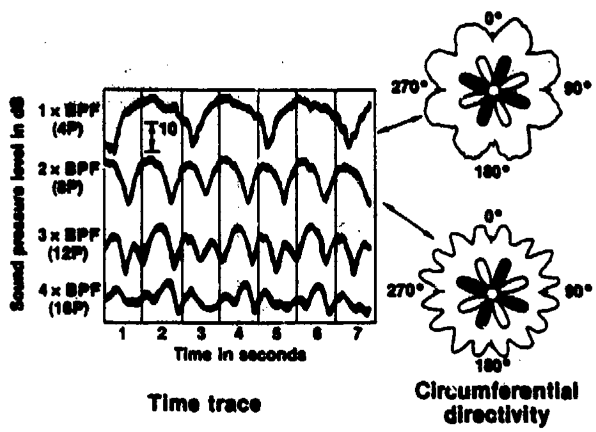


Fig. 4.9 Counter-rotating propeller circumferential directivity at blade passage frequency and higher harmonics (from Ref. 31)

Separation of Propeller and Engine-exhaust Contributions based on Pressure Time Histories

A piston-engine powered propeller-aeroplane radiates noise from the propeller and from the engine. Since the engine "firing frequency" and the propeller blade frequency are often harmonically related, it may be difficult to separate one from the other. For near-field flight noise testing it is particularly desirable to separate these two to evaluate the relative noise contributions and their dependence on flight operational parameters of interest. Such tests should preferably be done on the flying aircraft.

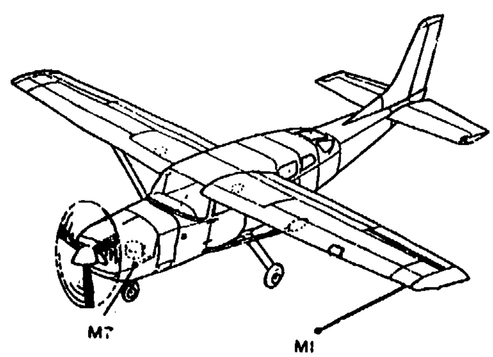


Fig. 4.10 Test aircraft Cessna T207 with microphones for propeller near field noise studies

A procedure is described in |32| where the two sources - after proper identification - are electronically separated to obtain the "clean" propeller signal at a predetermined observer position, in this case at a wing-tip microphone. Fig. 4.10 shows the test aircraft and its sting-mounted microphones on the wing. Here 'M1' designates the wing-tip microphone. Another microphone, 'M7', was positioned very close to the engine exhaust orifice. From the tape-recorded data, the "exhaust-noise signal was subtracted from the combined signal after appropriate adjustment in amplitude (to account for the propagation path attenuation from the exhaust to the wing-tip microphone) and in phase (to account for the sound propagation time). Fig. 4.11 illustrates this process: (a) shows the engine exhaust signature of the 6-cylinder-engine measured very closeby to the exhaust outlet - the repetitive pattern for the 6 peaks is clearly discernible; (b) represents the combined signature; (c/left) shows the (adjusted) exhaust signature superimposed on the "contaminated" total signature and (c/right) the "clean" signature of the propeller only, after subtraction of the exhaust-noise.

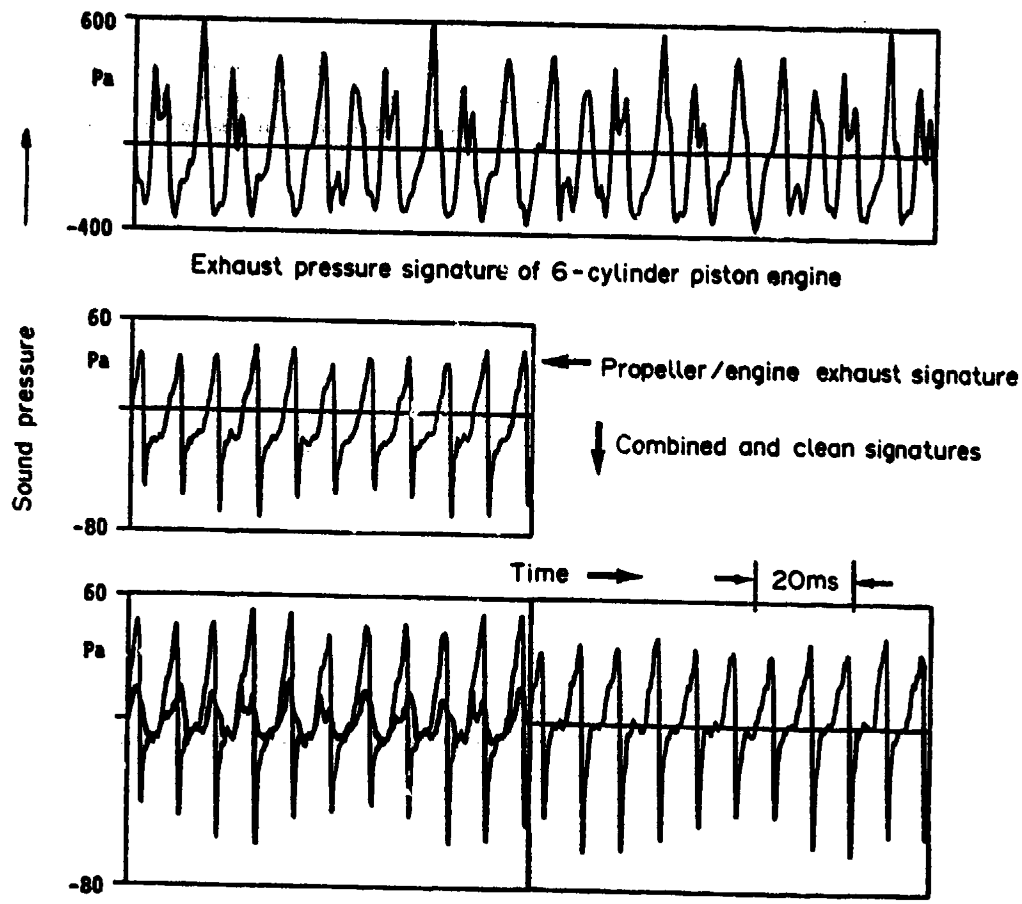


Fig. 4. 11 Procedure to extract the "clean" propeller noise signature from a signature containing both propeller and engine exhaust contributions

This approach is useful when the gear ratio between the engine and the propeller is such that a direct source identification of the propeller and engine rotational frequencies is not possible.

Determination of Real-time Blade-Pitch Setting

Variable pitch propellers automatically adjust their pitch, depending on the instantaneous load on the propeller. There is, however, no direct indication in the cockpit of the blade-pitch since there is no "need to know" for the pilot. In research it is sometimes of interest to monitor not only the average blade pitch angle but also its variation with time, since there is a direct bearing on the noise produced.

For that purpose one could project a narrow beam of light towards the rotating blade which has a narrow strip of reflecting tape at the appropriate location. The ratio between the duration of time where light is reflected and where no light is reflected is an indication of the blade-pitch angle; steeper angles thus cause shorter reflection blips, and vise versa. Since such optical information can be readily recorded on tape together with any acoustic information of interest, a direct correlation between these parameters is possible.

4.3.2 Fly-by Testing

In the technique of "fly-by testing" both the test object (the propeller aeroplane) and the microphone - attached to a companion aeroplane - fly in formation. This can be done at almost any desired relative speed - including zero - and at any relative position with respect to each other (Fig. 4.12).

Flyby testing offers the following advantages:

- o realistic flight condition
- o absence of ground proximity effects, such as
  - microturbulence due to solar heating
  - strong temperature gradients near to the ground
  - a ground surface atmospheric boundary layer
- o absence of ground reflection to the microphone
- o absence of pronounced atmospheric temperature differences between source and receiver
- o generally similar wind conditions for both the "test-" and the "receiver"-aeroplane
- o very low ambient noise (only aerodynamic noise induced by the microphone) especially when a glider plane is used as a pacer aircraft
- o possibility of effectively shielding engine exhaust noise contamination by flying at the "exhaust-averted" side of the test aeroplane

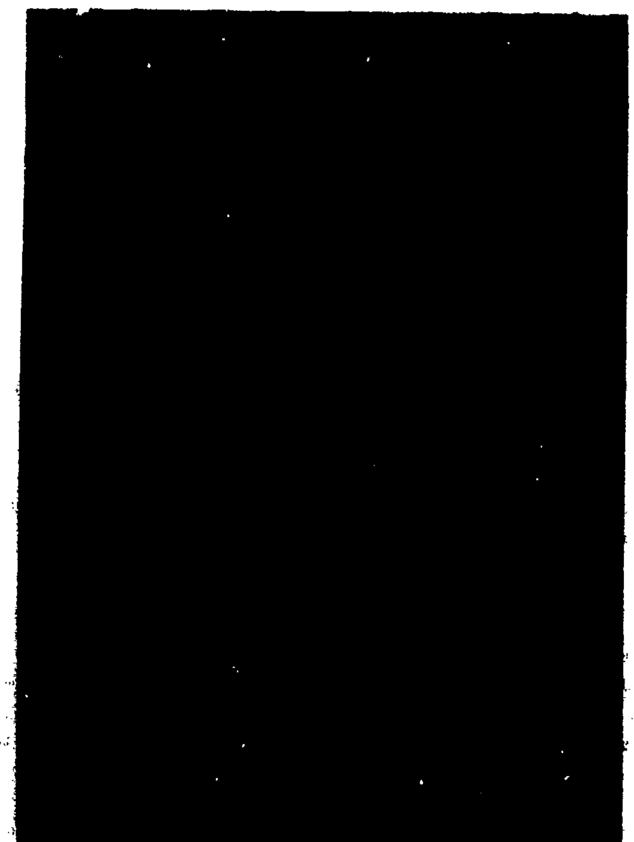


Fig. 4.12 Flyby testing: Formation flight of test-propeller-aeroplane (rear) and measuring glider aeroplane (front)

Tests employing a powered glider (whose engine was turned off during testing) to carry the measuring microphones |33| showed the feasability of this approach (Fig. 4.13). The test propeller-aircraft, a single-engine Jodel, passed the glider at a relative speed of 100 km/h, i.e. much less than the actual flight speed of the Jodel (230 km/h) and at a distance of approximately 100 m. An important advantage of this slow relative speed is that the radiated noise signature changes more slowly than when the microphones are on the ground. The figure shows the propeller noise pressure-time-histories during three successive 80 ms time intervals, where the glider was ahead, beside and behind the test aircraft, respectively. The changes in pulse width, amplitude and/or crest-factor of the individual pulses as a function of radiation direction are evident.

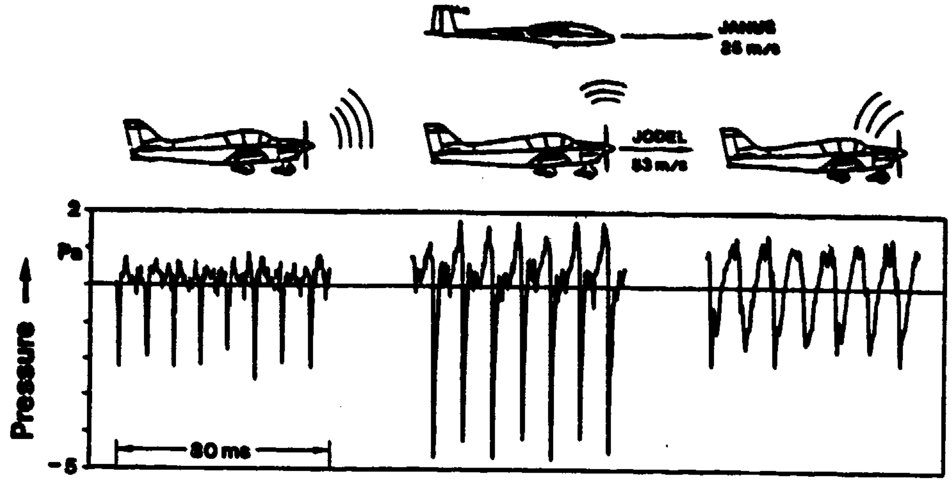


Fig. 4.13 Propeller noise pressure time histories as observed at angles 'forward', in-plane' and rearward' during flyby with propeller M_{hel} = 0.79 (from Ref. 33)

4.3.3 Flyover Measurements

The most widely used test procedure to study the noise of full-scale propeller-driven aircraft is the flyover test, as also employed in noise certification. The aircraft flies over the acoustic measurement station on the ground at a specified flight height. Possibilities to obtain incorrect data by such a procedure are, however, manifold and the acquisition, analysis and interpretation of acoustic data must be conducted in a very careful manner.

Data acquisition techniques and procedures largely correspond to those employed in noise certification testing. Data reduction is, however, often conducted in a different way, depending on the problem at hand. For example, data may be analysed in narrow-bands to facilitate identification of individual noise sources. It should be remembered that a flyover noise signature is inherently of transient nature and certain precautions are necessary to obtain correct narrow-band spectra from a flyover noise signature, as it is affected by a Doppler-frequency shift.

(a) Narrow-band Analysis of a Transient Flyover Noise Signal

Analysis Considerations

During a typical flyover, the (unweighted or A-weighted) noise level will increase, sometimes rather rapidly, from the ambient noise level to a maximum and drop back into the ambient. The frequency content of the observed signal will also change, because of the directivity of the source and the Doppler-effect. For a narrow-band analysis relatively small time-increments must be chosen, as both distance and slant angle with respect to a ground based observer change rapidly.

The fundamental tone of the propeller noise appears in the frequency spectrum as the product of the number of revolutions per second and the number of blades; harmonics are multiples of this fundamental frequency. For the ground based observer, this fundamental propeller frequency (and all harmonics) changes during the flyover. For a level flyover situation, the observed propeller noise fundamental is identical with the actual propeller noise fundamental at the moment when the observer receives the sound that was radiated in the plane of rotation of the propellers.

If the propeller RPM is not monitored in the cockpit the propeller rotation speed can also be determined from a plot of observed rotational frequency vs. time, or vs. radiation direction. When the aircraft flies at low speed or at a fairly large height, i.e in a manner such that the emission angle changes slowly with respect to a ground based observer, the propeller rotational speed can simply be taken as half the average of the almost constant frequencies during approach and during recess, respectively, as illustrated in Fig. 4.14 |34|.

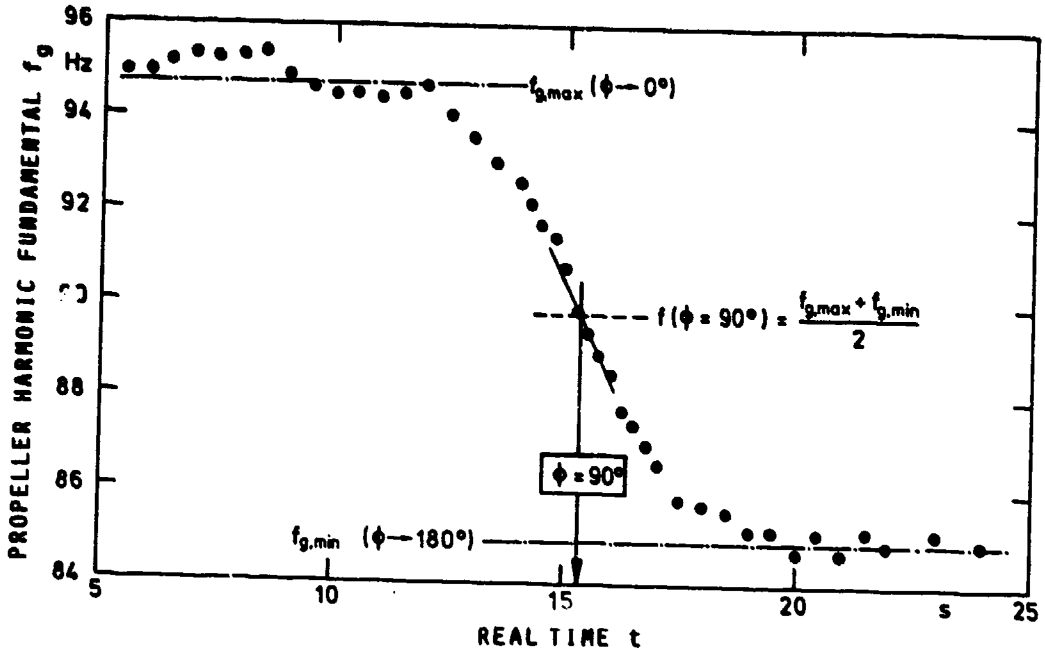


Fig. 4.14 Change of propeller rotational frequency due to the Doppler-effect during level fly-over as observed on the ground

F[illegible] example, one may now analyse the flyover noise signal at desired time intervals, e.g. every 1/2 second . However, since the signal is non-stationary, the analysis duration must necessarily be rather short. There is a relationship between the frequency band range to be analysed, specifically the upper frequency limit f_{ul}, the resolution in terms of an analysis-band-width Delta f, and the minimum required analysis duration Delta t.

One particular commercially available narrrow-band real time analyser can resolve a frequency band range into 512 points. Thus, if the frequency band of interest was 0 Hz to 1600 Hz, the analysis bandwidth Delta f (i.e. the resolution) is 1600/512 = 3.125 Hz. If the frequency band of interest was 12500 Hz, the resolution is 25 Hz. If a high resolution is required the frequency band range must b[illegible]rowed. There are other commercially available analysers with different resolutio[illegible] such [illegible] points or 400 points.

The analysis time, i.e. the time within which the complete narrow-band spectrum can be evaluated, depends on the sampling rate. For a frequency band of 1600 Hz and a resolution of 512 data points, each data point can be detected within 156.25 µsec. The entire spectrum would then require 512 x 156.25 µse[illegible] [illegible]. about 80 milliseconds. For a frequency band of 3200 Hz (with the corresponding analysi[illegible] width of 6.25 Hz) the sampling rate would be 78.125 µsec; hence the entire spectrum would [illegible] available after about 40 milliseconds. Thus, in this case the product of sample time and frequency band range is constant and equals 2^7 = 128. Fig. 4.15 shows the sample duration and the frequency resolution as function of the frequency band.

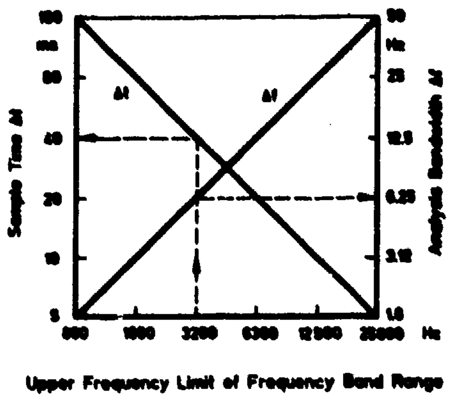


Fig. 4.15 Dependence of sample time 'Delta t' and analysis bandwidth 'Delta f' on the frequency band range

In order to increase the statistical confidence it is better to analyse the transient signal on the basis of several successive samples. Whether this is feasible depends on the characteristics of the signal time history, in particular on its slope with time. If the signal changes very rapidly, then only few analysis samples, e.g. 4 can be made, leading to 4 x 80 ms = 240 ms, or roughly a 1/4 second of analysis time during which the noise level may change by one or two dBs. Taking more samples to increase the statistical confidence would dangerously lengthen the analysis time. Thus, when analysing a transient (flyover) noise signal from one measuring microphone only, the combination of frequency band and statistical confidence must be carefully selected. Employment of several longitudinally spaced microphones will again help in analysing a transient signal as previously discussed in 4.2.2(c).

Separation of the Propeller and Engine Contribution based on Frequency Spectra

Fig. 4.16 shows flyover narrow-band spectra, taken at 2 second intervals from an ultralight aircraft (see |34|); both propeller noise and piston-engine exhaust noise contribute to the signal. The frequency band range was 0 to 1600 Hz, with a corresponding analysis bandwidth of 3.125 Hz. The propeller rotational blade fundamental was known, as was the engine firing fundamental frequency. The gear ratio was such that these frequencies were not related. Thus it was possible to differentiate between propeller and engine-contribution in an unequivocal manner. Similar spectra had been obtained over the entire time span of the flyover. The contributions of each harmonic of the propeller were added to obtain the overall propeller-noise level, and those of the engine to obtain the overall engine-noise level. The time histories of both (A-weighted) propeller and engine noise levels are shown in Fig. 4.17. The sum of these two is also shown, together with the originally measured signal. The latter is clearly higher than the sum of the propeller and the engine harmonic (!) contributions. The difference must be attributed to broadband-noise sources from the propeller and the airframe.

A propeller or a turbine emits noise not just as a consequence of blade thickness or blade loading, but also because it sheds vorticity, which emits sound as it is convected downstream in the wake flow. The fact that the wake flow is also noisy implies that the overall 'noise source' would be downstream of the propeller. When speaking of 'location' of a source of sound some care should be exercised. Given a sound field, there are many possible source distributions which could generate it. Among these 'equivalent' model sources, the identification of the real source of sound may not be an easy task, unless there is some 'a priori' knowledge of the sound generation mechanism. In the latter case we could, for example, distinguish the noise radiated by the propeller from the noise emitted by vorticity in the wake; the latter should have a continuum spectrum, since a range of flow velocities and Doppler shifts are possible in the wake flow. This example illustrates, how a narrow-band analysis of transient flyover noise of propeller-driven aeroplanes can be used to study noise contributions from different sources on an aircraft, i.e. propeller harmonic, engine harmonic, and aircraft broadband sources. It should be emphasised that the data shown in the previous figures were all obtained by means of inverted microphones above a ground board, the arrangement as shown in Fig. 3.47b. The analysis would have been much more complicated, if the customary microphone position 1.2 m (= 4 feet) above ground had been used. This problem is the subject of the following section.

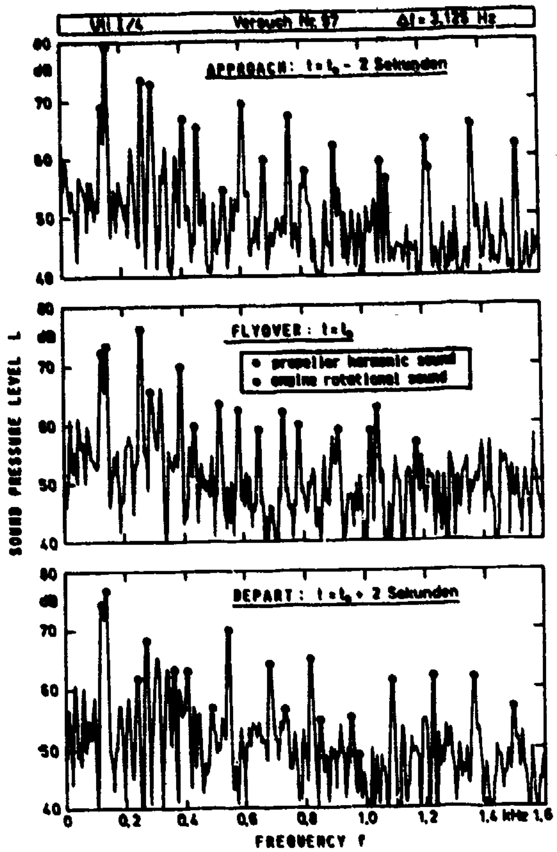


Fig. 4.16 Flyover noise narrowband spectra with propeller (e) and engine (o) contribution

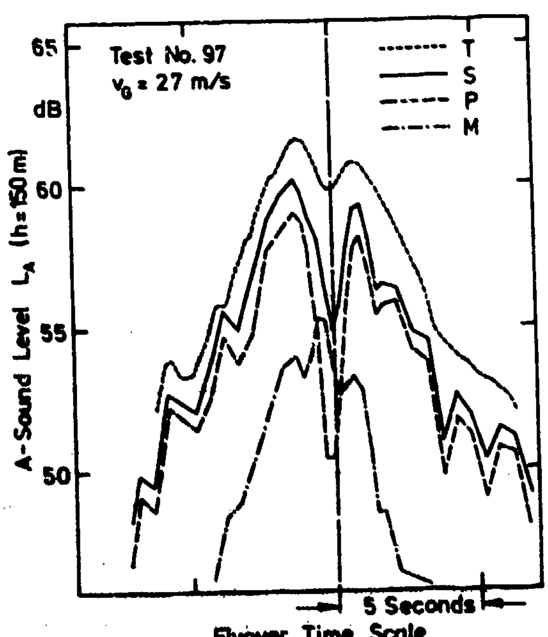


Fig. 4.17 A-weighted flyover noise time histories for propeller(----), engine (-.-.-), sum of both (——) and total measured including other sources (····)

(b) Microphone Ground Reflection Effects

The general problem of interference between directly incident and ground-reflected sound waves as radiated from an aircraft in flight is illustrated in Fig. 4.18. Numerous papers |35 - 39| have addressed this problem. The following discussion is largely based on |40|.

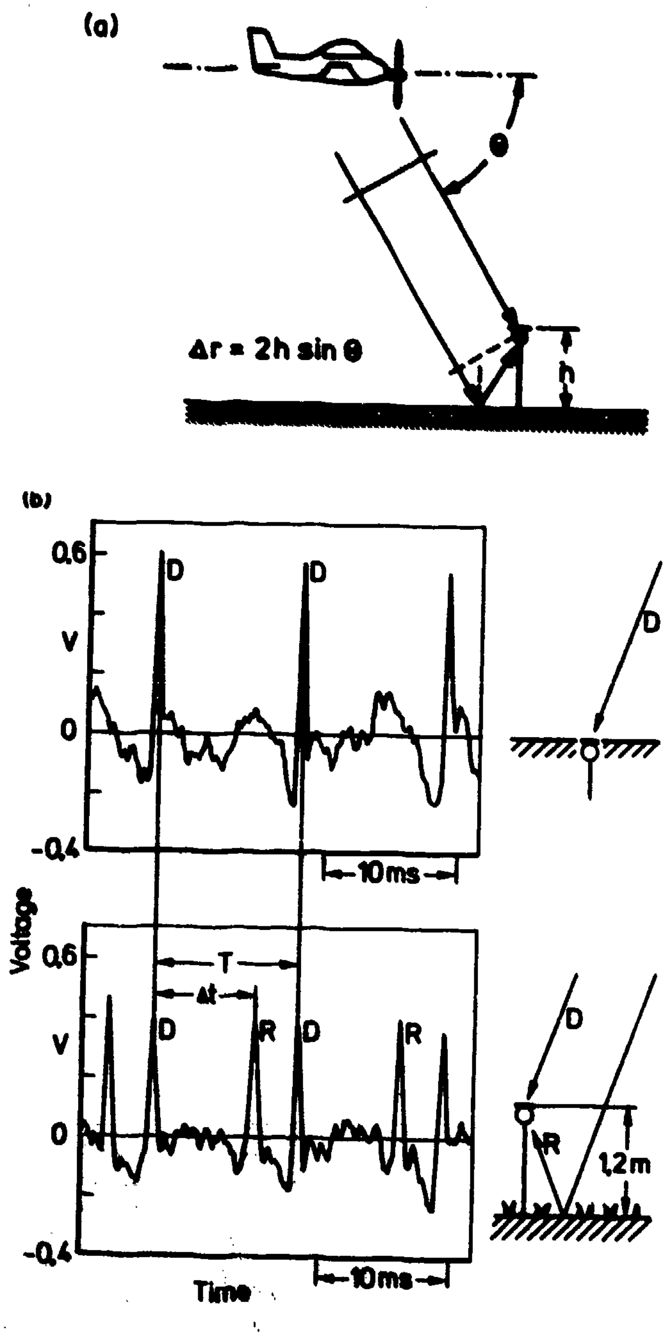


Fig. 4.18 (a) Schematic representation of ground reflection interference problem ;
(b) Appearance of the direct (D) and the ground reflected (R) signal on a microphone positioned some distance above the ground

If direct and reflected sinusoidal pressure waves with path length difference Δr and wavelength λ interfere, the acoustic pressures at the microphone show frequency-dependent differences from those of the directly incident wave. Pressure doubling - corresponding to an increase of 6 dB - will occur, when the ratio Δr/λ assumes values of 1, 2, 3, etc.; alternatively, a pressure cancellation - corresponding to a decrease by -∞ dB - will occur when the ratio 2 · Δr/λ assumes values of 1, 3, 5, etc. The periodicity of this interference depends on (i) the microphone height above ground, (ii) the ambient temperature, and (iii) the sound incident-angle.

An increase in the microphone height would thus reduce the frequency difference between these various maxima and minima, and vice versa.

Another important parameter that affects the shape of the interference function is the analysis bandwidth. The interference shown in Fig. 4.19 corresponds to a frequency analysis with an infinitely narrow bandwidth. Increasing this bandwidth results in a "slurring" of the maxima and minima. The upper-bound is a frequency-independent level increase of 3 dB (provided that the integration was extended over the entire frequency-regime with a white noise source). If the noise signature contains pronounced tonal components, as in the case of propeller aircraft, the measured noise spectrum is strongly affected by the relation

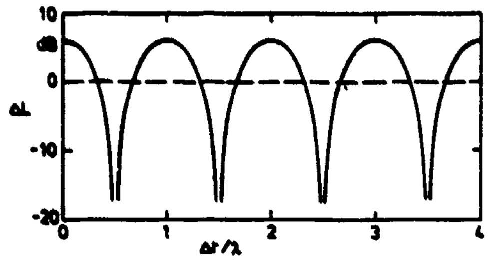


Fig. 4.19 Normalised representation of interference function referenced to free-field condition (from Ref. 40)

of the periodicities of the propeller rotational harmonics and the interference function.

Fig. 4.20 illustrates two examples of ground-reflection distortions in the propeller flyover noise spectra obtained from microphones 1.2 m above a (grassy) ground. Coincidence of the ground-reflection amplification frequencies in the interference pattern and the harmonic frequencies, as shown in Fig. 4.20a, represents a rare and rather coincidental case. The more frequent and typical situation appears in Fig. 4.20b, where seemingly erratic level changes of the first few rotational harmonics may be observed.

- High-frequency Broad-band Noise Correction

Attempting to correct such a measured spectrum to compensate for ground reflections raises one major problem: When comparing the shape of the ground reflection interference - as calculated on the basis of geometric acoustics - with the measured spectrum, one obtains (calculated interference caused) level-differences of more than 25 dB; measured level-dips - caused by reflection effects - on the other hand amount only up to 15 dB at high frequencies. In this case the prevailing noise floor would "fill" the level dips. Reflection corrections on a purely theoretical basis would thus necessarily lead to erroneous results, unless a proper interference integral calculation is performed; the latter takes into account phase differences and cancellation or reinforcement effects between several wave components, and involves a calculation less straight forward than a simple superposition of direct and reflected waves.

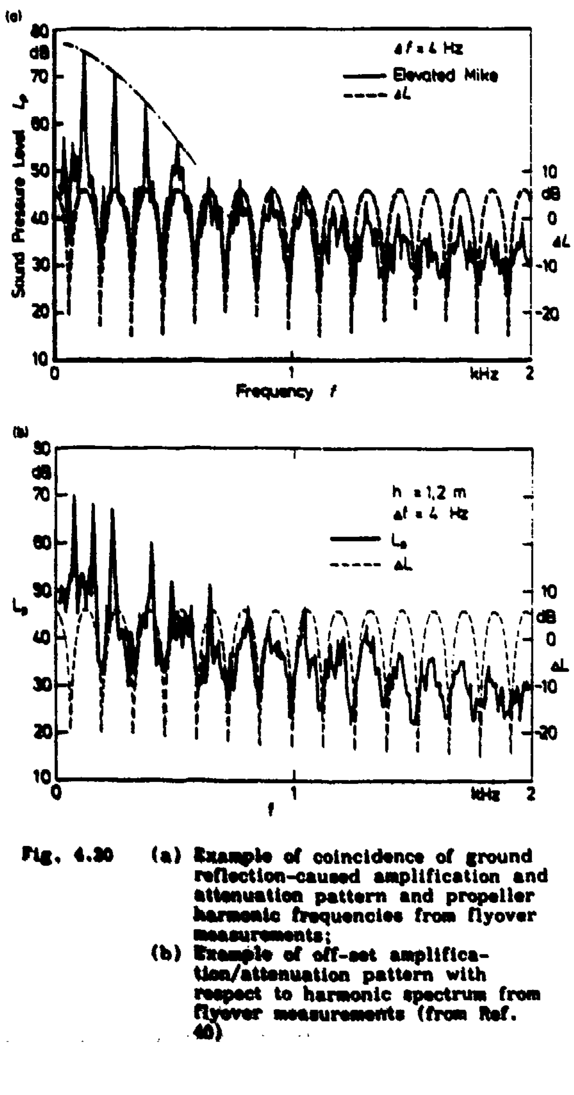


Fig. 4.20 (a) Example of coincidence of ground reflection-caused amplification and attenuation pattern and propeller harmonic frequencies from flyover measurements;
(b) Example of off-set amplification/attenuation pattern with respect to harmonic spectrum from flyover measurements (from Ref. 40)

Thus, a signal-to-noise ratio of 10 dB(A) - as required for the ANNEX-16 certification - does not suffice for a theoretical reflection correction. Worse still, it is next to impossible to even realize the necessary narrowband signal-to-noise ratio in excess of 30 dB. In consequence, one can not expect that a correction of the high frequency (quasi broadband) propeller noise component will lead to the commonly adopted -3 dB level difference in reference to the ground located microphone, but rather to some lesser value, such as -1 or -2 dB, depending on the actual signal-to-noise situation.

- **Low-frequency Tonal Correction**

In correcting these particular low frequency rotational noise components, which significantly contribute to the maximum A-weighted flyover noise level, one should be aware of the extreme level gradients within this interference function as apparent in Fig. 4.21.

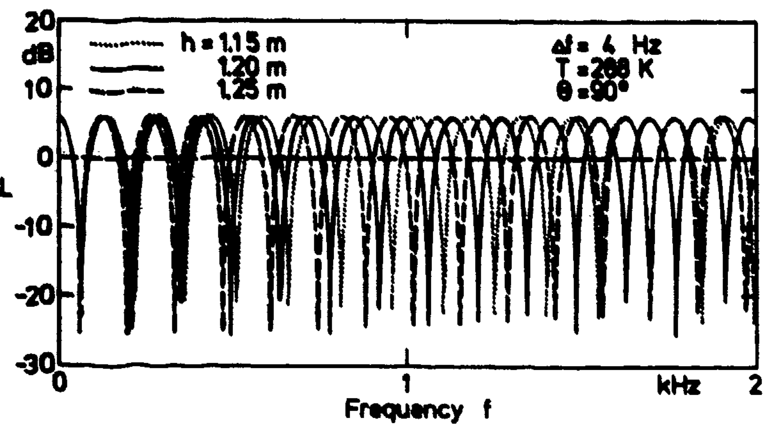


Fig. 4.21

Ground reflection interference function for different microphone heights above ground (from Ref.40)

The significance of these steep gradients on the accuracy of a possible subsequent reflection correction is twofold:

- The attenuation of a "destructive interference" very close to a rotational harmonic is influenced by both the spectral width of the particular harmonic and the characteristics of the filter network.
- Flyover noise measurements employing microphones with nominal heights of 1.2 m show the acoustically effective microphone heights to differ significantly. Even if the flyover-angle where the maximum A-weighted level occurs had been accurately determined, acoustically effective microphone heights between 1.15 m and 1.30 m were calculated based on the destructive reflection-interference frequencies. Not in every case do the interference patterns in narrowband flyover-noise spectra show up as clearly as in Fig. 4.20a. The relevant interference pattern for a subsequent reflection correction cannot normally be recalculated. Even a small deviation in microphone-height or in flyover-angle may thus result in large level differences in the vicinity of the destructive interference frequencies as obvious from Fig. 4.20b.

4.4 Flight Noise Testing of Helicopters

Of all flight vehicles, the helicopter has probably the most complex aeroacoustic source mechanisms. Both the main rotor and the tail rotor act as individual noise sources, but they also interact aerodynamically, giving rise to additional source mechanisms. To study these sources - impulsive type sources in particular - in detail, similar techniques are used as in the study of propeller-aircraft noise. For nearfield in-flight noise studies, microphones can be attached to the helicopter so that the receiver positions are well defined. Alternatively, the formation-flight technique is used, where the microphone-carrying aircraft flies parallel to and at some distance from the test helicopter, allowing farfield noise studies under realistic conditions. Thirdly, conventional flyover measurements are conducted, where the sound radiated by a helicopter in flyover is measured on the ground. The advantages and disadvantages of these flight noise measurement techniques have been discussed previously. In the following, a few examples of the first two techniques are presented.

(An excellent survey on the state of the art of helicopter noise research - including flight testing - appears in |41|).

4.4.1 Quasistationary Tests by means of Helicopter-mounted Microphones

In a joint US-Army/Bell-Helicopter-Textron research program on helicopter rotor aerodynamics and aeroacoustics |42|, an AH-1G test helicopter was equipped with several "nose-cone protected" condenser microphones (Fig. 4.22). They were located on a boom, on the left and right wings and aft on the ends of the elevator. Since the flow in the vicinity of a helicopter rotor is highly unsteady and frequently changes direction a swiveling support was used for the microphones. They could then find their own 'minimum drag alignment' to reduce the aerodynamically induced microphone self-noise.

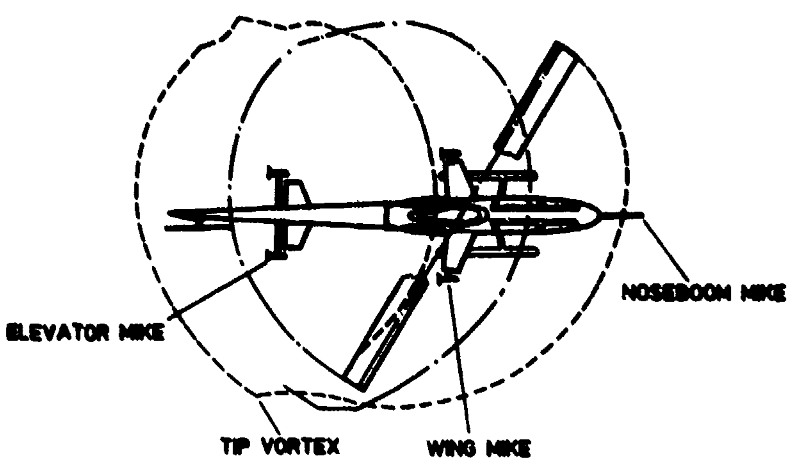


Fig. 4.22 Helicopter mounted swivelling microphones for near field noise studies (Bell-Helicopter/Textron Test)

Such microphones inherently measure noise at one point. No survey to investigate a directivity pattern is possible. Also, the microphones are rather close to the source, certainly in areas were near-field and far-field conditions intermingle. This makes interpretation difficult. A typical example of data is shown in Fig. 4.23. Pressure time histories (PTHs) are shown for one main rotor revolution under a condition of blade/vortex-interaction (BVI) impulsive noise ("blade slap") measured by the right-wing microphone and at the nose boom microphone. The pronounced BVI-impulses are evident. The more sinusoidal underlying signal is probably a near-field effect due to the passage of each rotor blade. An advantage of this technique is the relatively larger distance of the boom microphone from the tail rotor, thus minimizing disturbing effects of the tail rotor on the main rotor acoustic signals. Since the signal, though very unsteady, is not of the transient type, data can be averaged to increase statistical confidence.

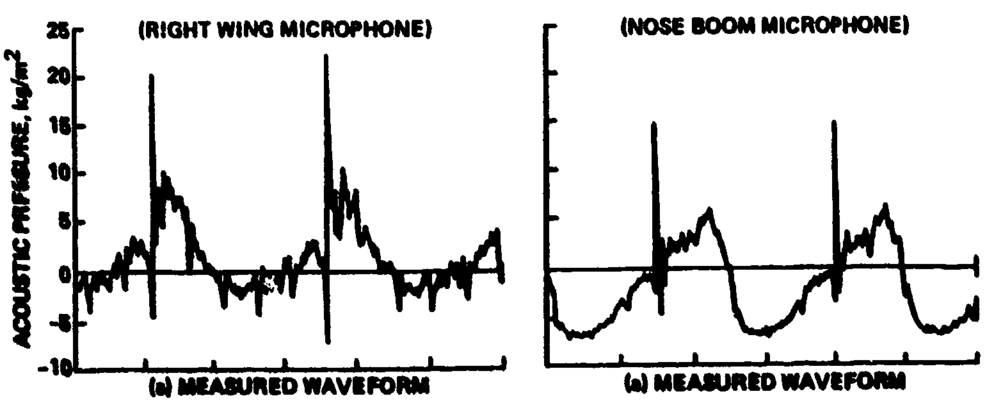


Fig. 4.23 Main rotor pressure time history measured through helicopter nacelle mounted microphones (from Ref. 42)

4.4.8 Inflight Noise Measuring Technique by means of a Companion Measuring Aircraft

The US Army has over many years perfected the technique of measuring farfield helicopter noise in the air using a quiet measuring aircraft which flies in formation with the test-helicopter |43|. Fig. 4.24 shows such a pair of aircraft in flight. The measuring aircraft (a YO-3A) is a propeller-driven reconnaissance aeroplane designed for very quiet operation. It was equipped with one nose-cone microphone on its tail fin, i.e. as far as possible away from the noise producing propeller.

Fig. 4.24 Formation flight measuring technique for helicopter in-flight noise research (US-Army)

Clearly, the measuring aircraft can again be positioned at any "fixed location" with respect to the test-helicopter. In the case at hand the two kinds of impulsive phenomena, namely 'blade/ vortex-interaction (BVI) impulsive noise', and 'high-speed (HS) impulsive noise' were to be investigated |44|. BVI noise predominantly radiates in a forward, downward direction. HS noise radiates forward and in the rotor plane. Hence, most test flights were conducted with the YO-3A in front of the helicopter, either in the plane of the main rotor or about 30 to 45 degrees down.

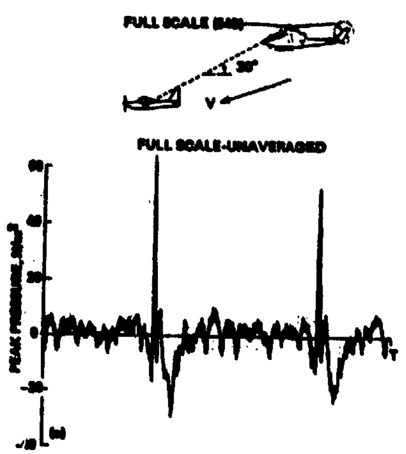


Fig. 4.25 Microphone on companion aeroplane sensing both main rotor blade-/vortex-interaction and tail-rotor acoustic signal

Station keeping is tricky and requires excellent piloting by both pilots. Good results are obtained when optical markings on the cockpit window are visually aligned with certain structural components of the measuring aircraft. A movie camera or video camera, or even a still-picture camera with fast exposure sequence, can be used to monitor the measuring aircraft position ahead. All picture or movie taking must be synchronised with the acoustic data

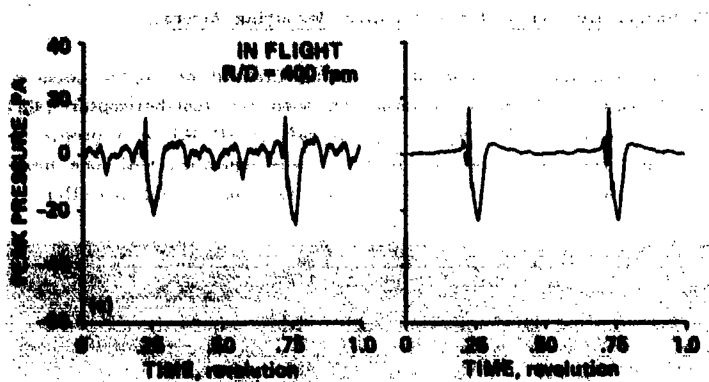
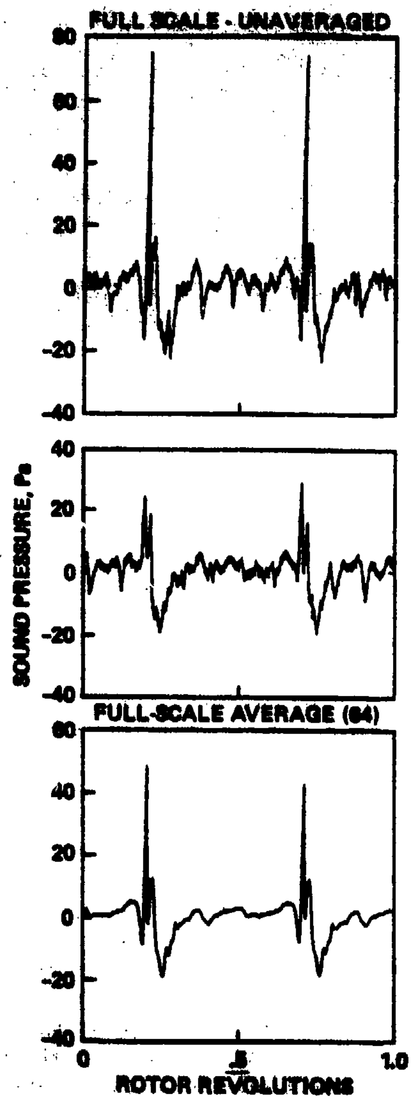


Fig. 4.26 Suppression of tail rotor contributions by trigger-locking onto main rotor signal

recorded on board the measuring aircraft by means of a radio-link, as had been discussed in Section 3.3.3 of this AGARDograph.

The microphone on the measuring aircraft senses the entire acoustic signature of the helicopter, i.e. its main-rotor and its tail rotor contributions and also any rotor interaction noise. A typical acoustic pressure time history of a helicopter is shown in Fig. 4.25. The components of the sound can be readily identified.



The data reduction technique can be taylored towards the particular acoustic phenomenon to be investigated |45|. For example, if a main-rotor related signal is studied in the presence of a disturbing tail-rotor signature, one can trigger on a pronounced main-rotor-related feature in the PTH such as the strongest BVI-peak. Then all non-BVI-related contributions are effectively suppressed, as shown in Fig. 4.26. Likewise, by locking onto an appropriate tail-rotor PTH-feature it would be possible to effectively suppress all main rotor related acoustic phenomena, if tail rotor acoustics is to be investigated.

Since the distance between the 2 aircraft and their relative positions cannot be accurately maintained it is unavoidable that the signal characteristics change slightly in the course of time. If the pilots are good the average general features should remain approximately unchanged. Here again, as the signal is not transient, it will be possible to average over many rotor revolutions (e.g. 64) to smooth the resulting signal and gain statistical confidence. A comparison of time histories shows the respectively highest and lowest peak amplitudes during one main rotor revolution, together with a 64-times averaged PTH. Fig. 4.27 shows the beneficial effect of that procedure.

Fig. 4.27

Comparison of two unaveraged and one (64-times) averaged sound pressure time histories for a time span of one rotor revolution

4.5 Jet Noise Testing in Wind Tunnels

Most aeroacoustic wind tunnels are too small to test full scale jet engines for noise under realistic low speed inflow conditions. Apart from the need to dispense with the exhaust gases from such an engine, which cannot be introduced into the tunnel flow circuit, the excessive heat of a realistic jet exhaust is difficult to dissipate, lest a substantial heating of the tunnel flow was accepted.

On the other hand there is a need to extrapolate static engine noise data to flight noise data as had been mentioned in Section 4.2.2 above in order to derive, for example, flyover noise data or more specifically noise certification data for jet-propelled aeroplanes. Again, model tests might be indicated in such cases. If the interest was specifically in the jet as such as the noise generator, appropriate experiments can be conducted in to-days aeroacoustic wind tunnels.

One such typical example will be described following |46|, where also a special testing technique had been introduced. The test concerned the evaluation of flight effects on jet noise sources. The investigation was conducted jointly by the Boeing Commercial Airplane Co. and DLR in the DNW. Specifically the effect of a surrounding fairly low-speed flow - as in take off or landing - on the "stretching" and "downstream displacement" of the actual noise sources of a hot circular turbulent free-jet was to be studied. In this context it should be recalled that the length of the sound-generating volume of a jet increases if the jet exhausts into a parallel flow. Here, the specific test objective was to determine the difference between the noise source distribution in jets with and without a co-flowing stream, employing a strictly acoustic and non-penetrating measurement technique. This lead to the use of a highly directional microphone system, the "acoustic mirror microphone" system.

4.5.1 Test Set-up

(a) Model Jet

The test set-up in the open test section of the DNW (Fig. 4.28) consisted of a hydrogen peroxide hot gas generator (developed by NLR) enabling the production of a high speed and hot (830 K)

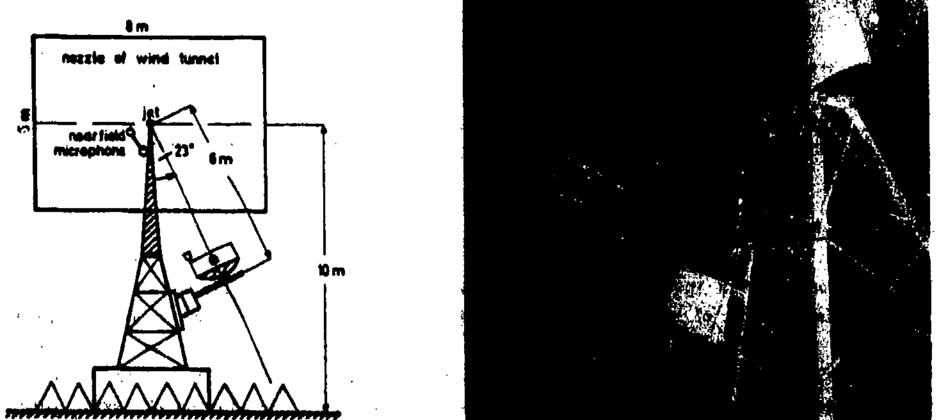


Fig. 4.28 Acoustic mirror microphone for model jet noise source localisation studies in the DNW

jet of 6 cm diameter, emanating into the surrounding environment; in the absence of tunnel flow this environment was the anechoic test hall, in case of tunnel flow this environment was the surrounding tunnel flow. Nozzle pressure ratios could be selected such that jet speeds from 320 to 500 m/s were attained.

(b) Mirror Microphone

The axial distribution of the sources along the model jet were determined with the highly directional acoustic mirror microphone also described elsewhere |47, 48, 49|. The particular microphone-system as described in Refs. 48 and 49 consists of a 1.6 m diameter concave elliptic mirror, where one (sometimes several) microphone(s) is (are) mounted in the near focus of the mirror. The mirror thus focuses the sound waves emanating from a volume element located in the far focus upon the image point of the source in front of the mirror (i.e. the near focus). By traversing the mirror microphone as a whole parallel and alongside the model jet axis one may follow the distribution of a source in any selected frequency band.

4.5.2 Data Acquisition and Shear Layer Effect Calibration

The acoustic mirror assembly must be positioned outside the free tunnel flow. In this test set-up, the mirror was 6 m away from the tunnel flow centerline thus clearing the free flow shear layer. Sound from the source to the receiving microphone passes through the shear layer, where it is refracted and scattered. This in itself causes an apparent downshift of the sound sources and also a reduction in gain and spectral resolution depending on the ratio of the acoustic wavelength and the turbulence scale of the shear layer.

In the subject study it was therefore felt necessary to calibrate the shear layer effects before data could be correctly interpreted. For this purpose a very small loudspeaker was used as a point source at the location where the jet source was to be positioned lateron. The loudspeaker was fed with broadband sound, filtered in octave bands from 1.0 to 31.5 kHz, thus providing information on the effect of the shear layer upon sources of such frequencies. The apparent downstream shift of sound source position as function of tunnel flow velocity is shown in Fig. 4.29.

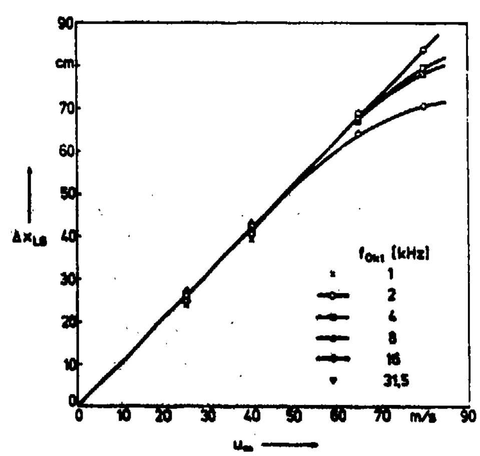


Fig. 4.29 Downstream shift of loudspeaker-generated tone source location in a hot model jet (from Ref. 46)

4.5.3 Test Results

When the model jet is in operation moving the mirror assembly alongside and parallel produces a "lateral" distribution of sound pressure level with a very pronounced peak interpreted as the "source" of sound for the selected frequency band. In Fig. 4.30 the case of no tunnel flow is shown. Here, model jet velocity is 500 m/s, jet temperature is 830 Kelvin and the octave band is 16 kHz. The level peak appears 2.6 nozzle-diameters downstream of the nozzle exit. Introduction of tunnel flow then shifts the sources downstream, as shown in Fig. 4.31. Here the conditions of zero- and of 80-m/s-tunnel flow speed are compared for a model jet velocity of 450 m/s. Clearly, a substantial downstream shift of the sources occurs.

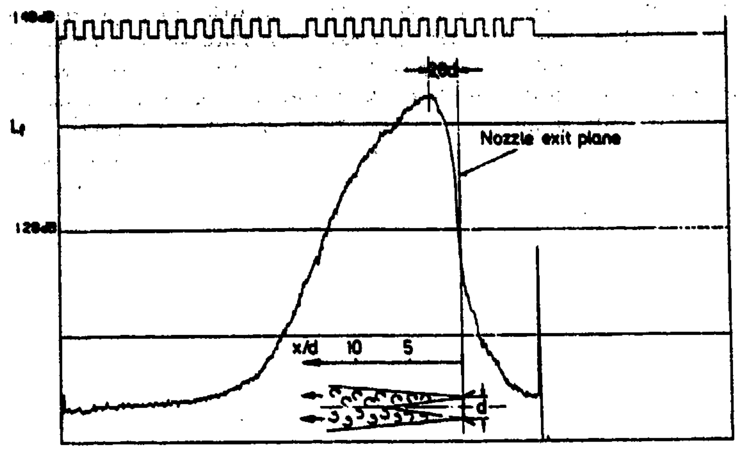


Fig. 4.30

Jet noise source location at 16 kHz for 6 cm diam. hot jet of 530 m/s speed (from Ref. 46)

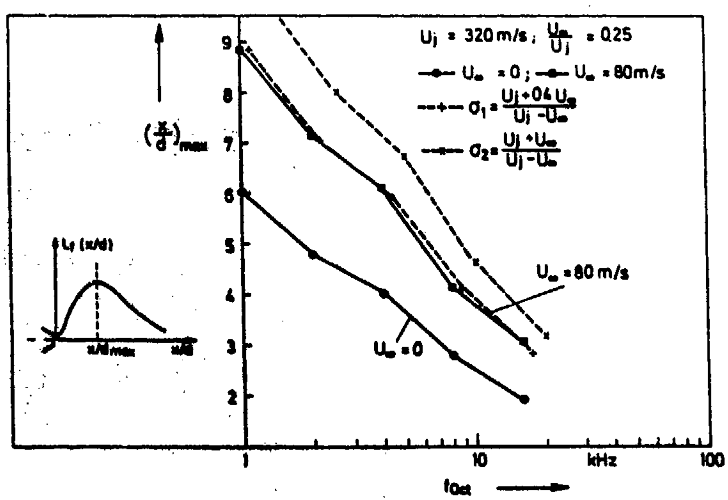


Fig. 4.31

Downstream shift of jet noise sources (from Ref. 46)

Such experimental findings are important in attempting to predict flyover jet noise from static data. The experiment demonstrates clearly that location and identification of sources of sound in a jet is very much affected by the flow properties.

Still, dedicated and controlled model jet noise tests in acoustic wind tunnels can significantly further the understanding of aircraft jet engine noise characteristics in flight.

4.6 Propeller Noise Testing in Wind Tunnels

Although flight testing provides the most realistic environment for noise-tests of a propeller , it is difficult to isolate the propeller contribution, as had been emphasized before. In basic propeller noise research it is often advantageous to first study the isolated and uninstalled propeller before dealing with the effects of integration and installation. For such studies, wind tunnel tests are ideal where a propeller can be operated without an "attached aircraft".

The German Dutch Wind Tunnel (DNW) was used in a joint DLR/FAA research project on the noise of full-scale General Aviation propellers |80|. The test program was initiated to clarify certain questions for the development of the new ANNEX 16/Chapter 10 noise certification procedure. It dealt with the effect of ambient temperature (≙ helical blade tip Mach-number) and of the attitude of the propeller rotational plane (inflow angle of attack) on noise. This angle changes during climb and descent. Based on the results, procedures were developed to correct noise levels from test temperature to reference temperature, and for oblique inflow into the propeller plane of rotation. Data acquisition and analysis of this test are described in the following.

4.6.1 Experimental Set-up

(a) Test Stand Specifics

In the experimental set-up, the (full-scale !) 2 m diameter 2-blade propellers were driven by a 360 kW electric motor in an aerodynamically shaped housing, supported on a pylon structure (Fig. 4.32). Approximately half-way between the 6x8 m² nozzle and the 9.5x9.5 m² collector (separated by approximately 20 m) the propeller could radiate sound into the anechoically treated test hall while still being completely surrounded by the clean tunnel-core-flow. The pylon could be turned such that the propeller rotational plane assumed angles of +/- 15° with respect to the oncoming flow. Ambient temperature could be varied by starting the test series (in winter) at low ambient temperatures (about 5 °C), and then letting the tunnel heat itself up to flow-temperatures around 25 °C.

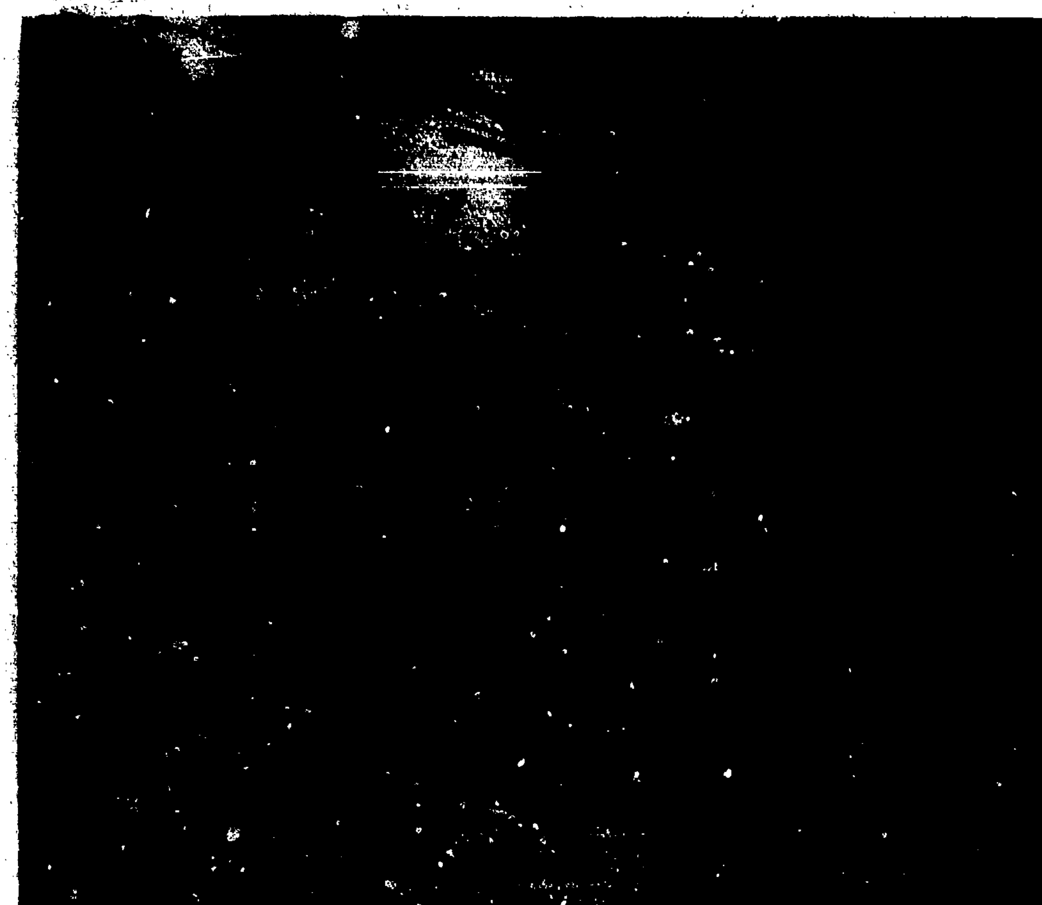


Fig. 4.32 Propeller noise test set-up in the German Dutch Wind Tunnel

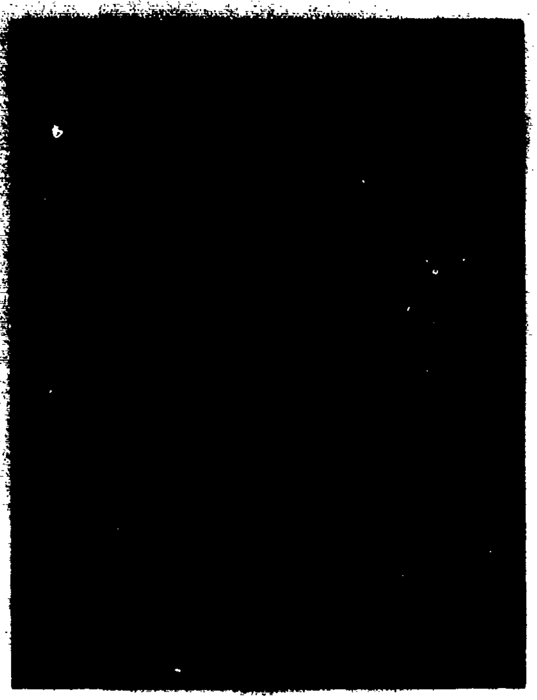


Fig. 4.33 Front view of inflow microphone arrangement in the DNW

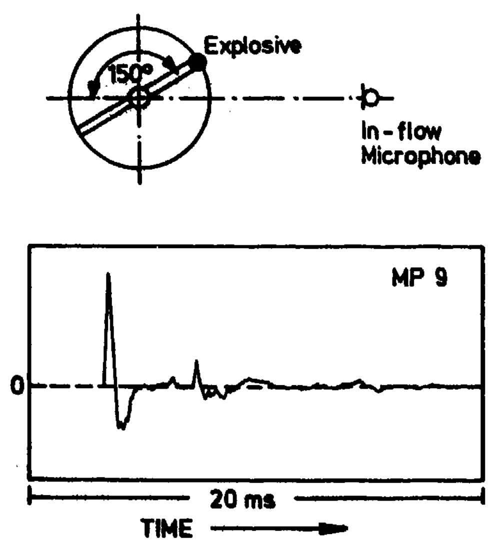


Fig. 4.34 Bang-test results for inflow microphone reflection check after exploding charge

The special arrangement of the inflow microphones should be noted (Fig. 4.33). Six microphones were positioned to one side of the propeller within the tunnel-core-flow. They were placed along a helical line in the downstream direction, so that the aerodynamic wake of an upstream microphone could not impinge on a subsequent microphone.

When conducting aeroacoustic wind tunnel tests on a pylon-mounted noise generator, it is important to check possible adverse reflections of the support surface structure. Bang tests are executed by mounting small explosive charges at the likely locations of acoustic sources. In the case of a propeller these are the blade tips. When the charges explode the microphones receive a direct signal and one, or several, reflected by nearby surfaces. Fig. 4.34 shows a typical bang-test result. On account of the time span between the explosion and the arrival of the reflected signal the location of any critical surface can be identified. Such surfaces must then be treated anechoically.

(b) Data Reduction Technique

In reducing the data, averaging is of paramount importance, as shown in Fig. 4.35. The unaveraged pressure time history (PTH) of the propeller signal, as measured at one of the side-line microphones, clearly shows the passage of substantially different sequential wave-forms caused by the blades. Some 50 of these instantaneous PTHs were individually analysed in narrow bands and the spectra subsequently averaged. The final spectrum - shown in Fig. 4.35a - exhibits a rather high noise floor.

By averaging, however, the PTHs first one obtains a much smoother PTH. Now, the subsequent narrow-band analysis shows a significantly reduced noise floor (Fig. 4.35b). In this spectrum many more harmonics can be seen. Since the problem was studied in the context of noise certification pertaining to overall A-weighted noise levels, it was important to have a sufficient number of harmonics in the frequency range around 1000 Hz available to determine an overall A-weighted noise level. Hence the second analysis-procedure is to be preferred.

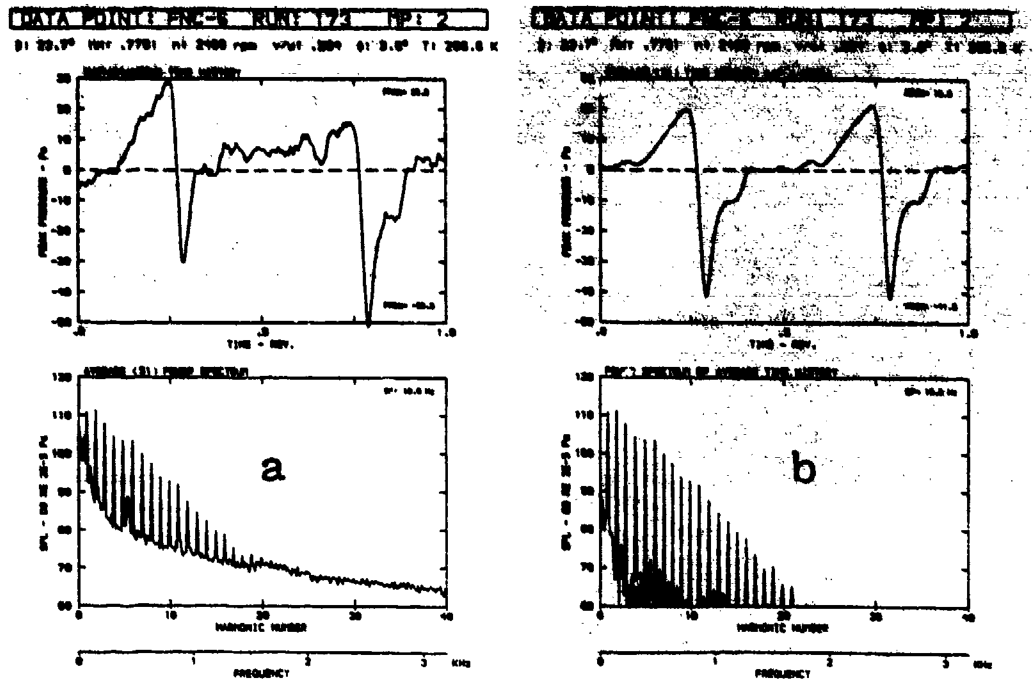


Fig. 4.35 Comparison of unaveraged and averaged propeller noise time histories with ensuing narrowband spectra

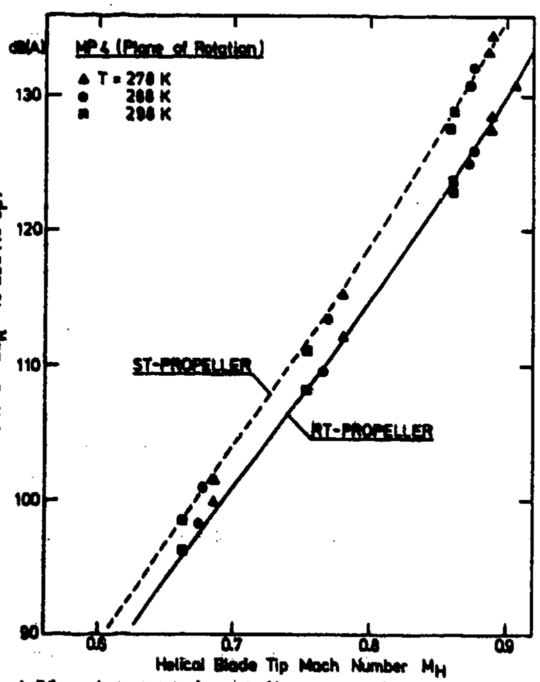


Fig. 4.36 A-weighted overall rotational noise levels vs. helical blade tip Mach number as measured in the plane of rotation and referenced to a source/receiver distance of one propeller diameter (from Ref. 51)

4.6.2 Experimental Results - Temperature Effect

The tests showed that the overall A-weighted noise levels in the plane of rotation was, to a good approximation, proportional to the 1.5th power of the engine power. Another - more influential - parameter is the helical blade tip Mach number, no matter how the three basic factors 'flow speed', 'rotational speed', and 'temperature' are combined. Fig. 4.36 shows that all data points from the above tests could be normalized on that basis |51|. Different temperatures were entirely accounted for by the helical blade tip Mach-number. It should be recalled, however, that for correction purposes, it is the helical Mach-number slopes (rather than the absolute levels) that are important.

The tests indicated that under the operational conditions of noise certification, a change in temperature will produce the same effect as a change in flight and/or propeller rotational speed. It can thus be concluded that the in-the-field determination of the "Mach-number"-dependence (see Fig. 3.49) is a feasible approach; it yields a better "temperature-correction" methodology than any "constant Mach number ratio to some power"-approach would offer, provided that the acoustic signal was entirely caused by the propeller as such. Any engine contribution over and above the actual propeller noise would necessarily invalidate such a relationship.

4.6.3 Experimental Results - Propeller Rotation-plane Attitude Effect

Acoustic data were also taken for different rotational plane attitude angles within a range of +/-7.5 deg. Other parameters varied were blade pitch angle, wind-speed and propeller rotational speed.

Comparing noise levels, as measured at different propeller plane attitude angles with those for a zero attitude (referenced to a fixed observer position and accounting for the angular radiation directivity) shows them to increase for positive values, and to decrease for negative values, of the attitude angle.

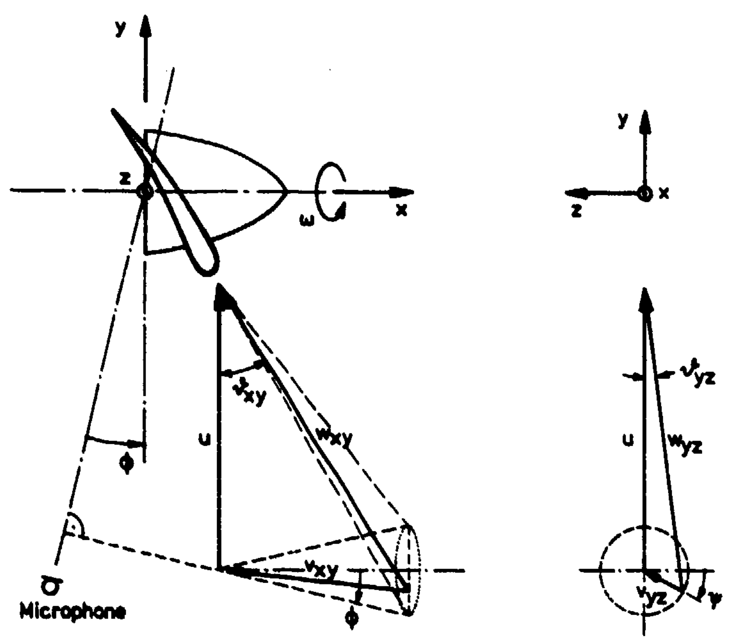


Fig. 4.37 Effect of inflow angle of attack into a propeller plane (from Ref. 52)

For a given microphone position, the predominant "noise source" is the propeller-blade advancing towards that microphone. It becomes obvious now that positive attitude angles result in an increase, negative attitude angles in a decrease of the effective blade pitch angle, as well as in helical blade-tip Mach-number. Referenced to the zero-attitude situation, the ensuing deviations in local blade angle-of-attack and Mach-number can be expressed as function of attitude angle and advance ratio for the particular instant in time when the propeller blade axis is orientated perpendicular to a connecting line between the propeller hub and the microphone. Fig. 4.37 illustrates the geometries of the problem.

Noise levels as measured at different attitude angles can now readily be plotted versus a "corrected Mach-number" (Figs. 4.38). All data points now fit one curve very well |52|.

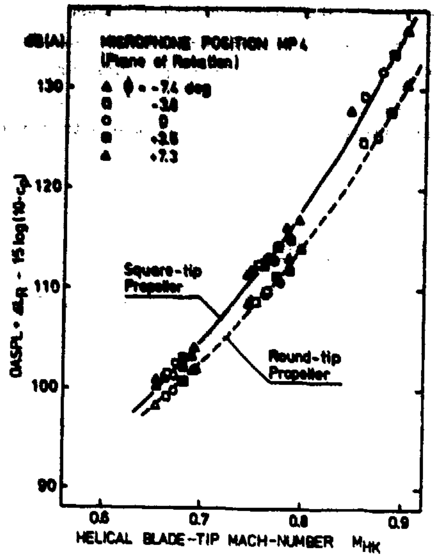


Fig. 4.38

Normalised A-weighted overall rotational noise levels vs. helical blade tip Mach number for different propeller plane attitude angles

4.7 Rotor Noise Testing in Wind Tunnels

Similar considerations as those in the previous section on wind tunnel noise testing of aircraft propellers apply to the testing of helicopter rotors in aeroacoustic wind tunnels. The flow field around a helicopter rotor is, however, much more complex due to the highly asymmetric inflow conditions of a rotor blade. This applies to both the main and the tail rotor.

As stated earlier, for aeroacoustic testing an open wind tunnel should be used and it should be verified that reflection of sound from any nearby surfaces is not significant, since situations may arise in which the reflected sound could predominate over the direct sound. Because of the highly unsymmetrical acoustic field around a helicopter rotor it is generally advantageous to employ many more microphones than would be required in a typical propeller noise test. Preferably, one or more continuously movable microphone array(s) should be employed.

Testing in an aeroacoustic tunnel allows the study of an isolated main rotor, of an isolated tail rotor, or a combination of these two to represent a realistic main-/tail-rotor assembly. Isolated main rotor tests can be justified because main rotor inflow is essentially unaffected by the presence of a tail rotor (at least in forward flight). This is not the case for the tail rotor. A tail rotor in the majority of cases operates in the aerodynamic wake of the main rotor; hence the study of isolated tail rotors would only be justified for hover conditions or, perhaps, for ascending (climbing) flight, where the main rotor wake is swept back some distance under the tail rotor. Specific problems thus require specific experimental arrangements.

(An excellent survey on the state of the art of helicopter noise research - including aspects of wind tunnel testing - appears in |41|, as mentioned before).

4.7.1 Isolated Main Rotor Noise Tests

In a joint US-Army/DLR main rotor noise study in the German Dutch Windtunnel |53, 54|, the impulsive noise phenomena of an isolated 1/7-scale model of a main rotor were investigated. These tests served two purposes: first, the basic source mechanisms were studied and, second, the scaling of wind tunnel model tests over the relatively large range of a factor of 7 to full-scale was checked. In fact, the flight tests described in Section 4.4 above provided the basis for comparison.

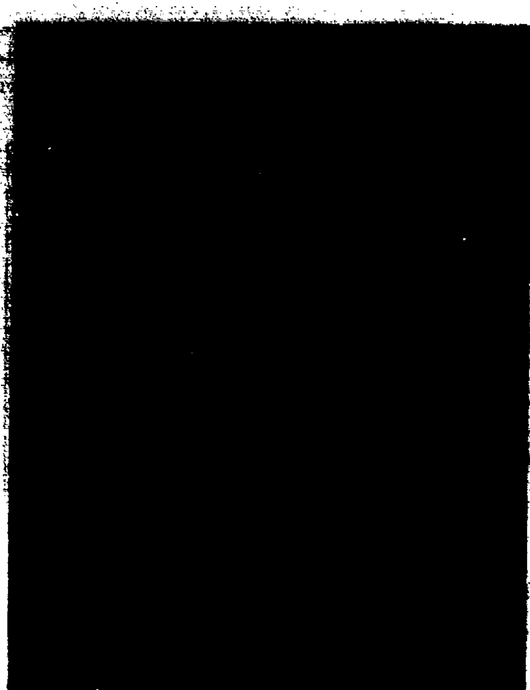


Fig. 4.39 Model main rotor test stand with ground-pylon support (US-Army/DLR test)

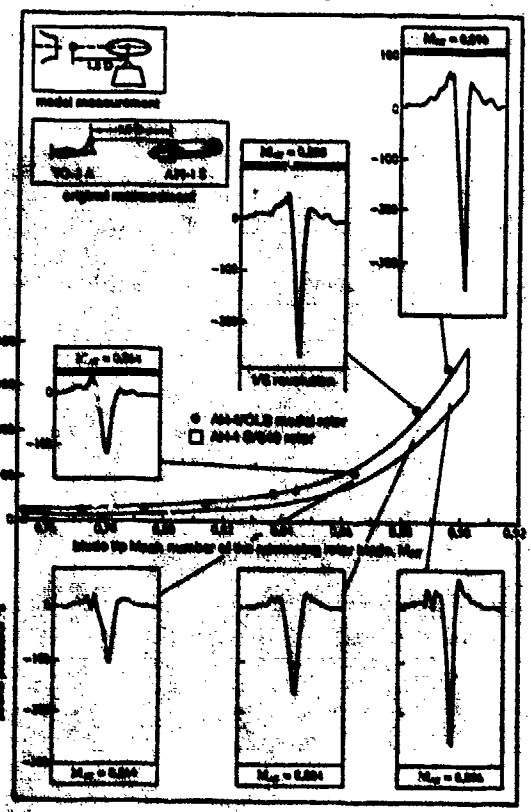
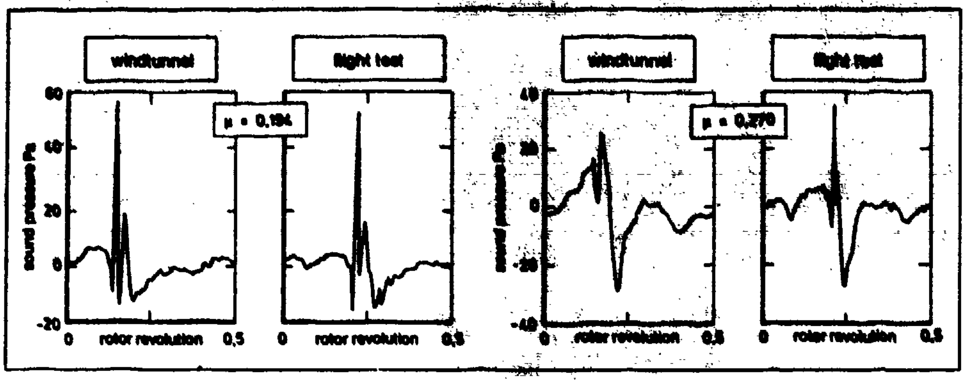


Fig. 4.40 Comparison of upstream inplane pressure-time histories for one blade-passage from wind tunnel model tests and full-scale flight tests (from Ref. 54 and 55).

In the test set-up (shown in Fig. 4.39), a very stable support structure was used and the rotor was further supported by a tubular pylon. Extensive bang-tests and subsequent covering of all critical surfaces with sound absorbtive material assured minimum reflections from these surfaces. Since only impulsive noise phenomena (high speed impulsive noise and blade/vortex-interaction impulsive noise source characteristics) were studied, the presence of the support structure directly under the rotor was not too detrimental; acoustic radiation of impulsive noise occurs essentially in a forward (upstream) direction. Three of the measuring microphones were mounted slightly below the rotor plane (to avoid wake impingement) and 6 additional ones in a forward-downward locations. The test results of this experiment have been widely published |e.g. 55, 56, 57|.

In the context of this AGARDograph it is of interest to discuss acoustic scaling. It was found that - if the Mach-number of the advancing blade was identical in the model and the full-scale test then full-scale and model-scale pressure time histories for the high-speed impulsive noise condition showed excellent agreement both in terms of wave -forms and amplitude (Fig. 4.40).

Scaling worked less well for the case of blade/vortex-interaction impulsive noise (Fig. 4.41). These phenomena are understandibly much more sensitive to geometrical and operational differences between full scale and model. The exact passage of a vortex-trail with respect to a rotating blade is significant for the occurrence and the strength of an impulsive peak. The Reynolds-number in particular may have a decisive effect on the location of such vortex-trails. Also, BVI-noise is not only a function of the advancing blade tip Mach number, but also of the inclination of the tip-path plane with respect to the oncoming flow (i.e. the rate of descent or climb) and the rotor thrust. The experiments show that a high advance ratio causes fairly strong discrepancies in the pressure time histories, though scaling worked well at low advance ratios. Thus, caution must be exercised with helicopter rotor models of small size in aeroacoustic wind tunnel tests.



a b

Fig. 4.41 BVI-impulsive noise pressure waveform comparison for model and full-scale at (a) low and (b) high advance ratios

To overcome such scaling problems larger models can be employed such as the one shown in Fig. 4.42, representing a 40%-scaled model of a BO 105 helicopter rotor in the DNW open test section. This test program was a joint venture of NASA and DLR |58, 59|. Though model size does help reduce scaling problems, the inherent disadvantage of large-size models is that the acoustic near field extends further out.

Fig. 4.42 a. 40%-model scale helicopter main rotor test set-up in the DNW

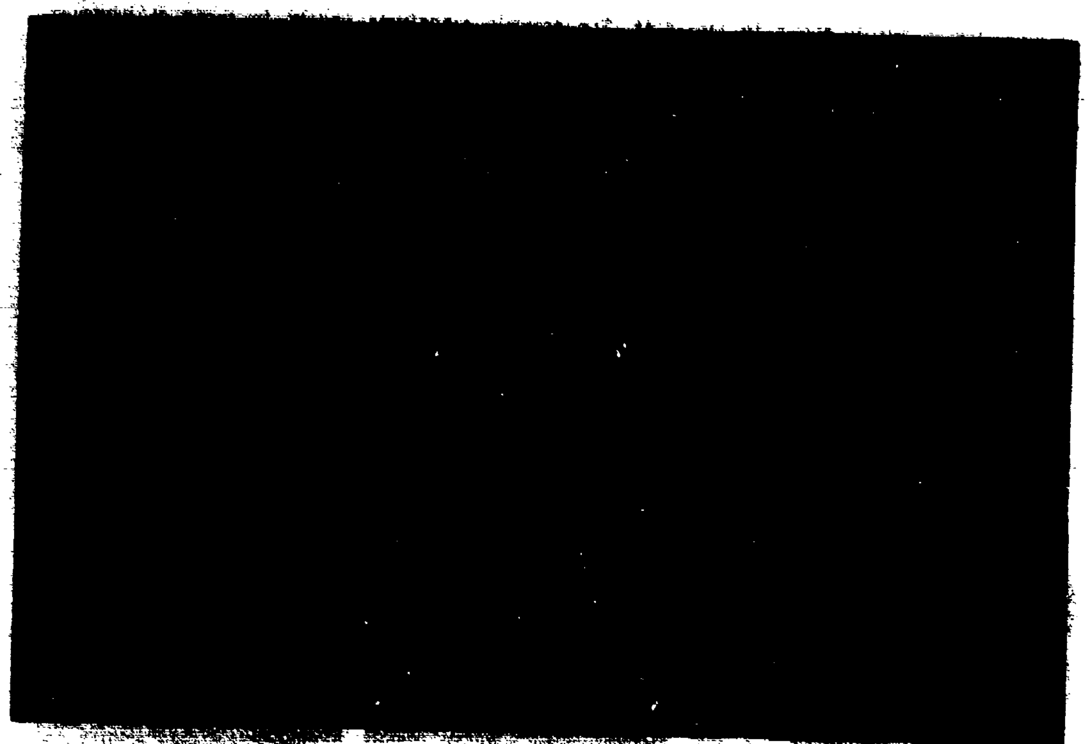


Fig. 4.42 b Same main rotor system as in previous figure equipped with compatible tail rotor

Thus the measuring microphones must be further away from the model if farfield measurements are required. Even in this large tunnel, the DNW, measurements outside the flow potential core would then be necessary so that the acoustic signals will have to pass through the free shear layer. The set-up shown in Fig. 4.42 has, however, a distinct advantage over that of Fig. 4.39: the very rotor is now supported by means of a tail-sting allowing entirely undisturbed measurements directly under the rotor, an area which is of prime interest in simulating a flyover situation. Also a microphone-carrying "wing-structure" that could be moved in a continuous manner under the rotor allowed data to be acquired over a very large area under the rotor.

A particularly interesting result from this test is shown in Fig. 4.43, where the sound field under the rotor is presented in terms of contours of equal peak-to-peak BVI-time history maxima |60|. Changing the rotor tip path plane and the rotor advance ratio shows the respective BVI-maximum to assume different locations and strenghts, depending on the particular combination of tip path plane and advance ratio, for otherwise unchanged parameters.

4.7.2 Main-/Tail-Rotor Interaction Noise Tests

The test set-up shown in Fig. 4.42 was complemented (within a DLR research program) by adding a tail rotor of the same scale. Both rotors are driven independently and the position of the tail rotor with respect to the main rotor can be varied 3-dimensionally. The entire set-up as attached to the tail-sting could also be inclined with respect to the mean flow direction. Thus, climbing, level, and descending flight can also be simulated.

A typical test result is shown in Fig. 4.44. The acoustic signatures (again in terms of pressure time histories) are shown below the rotor-system with both rotors operating. The left microphone shows both main rotor and tail rotor contributions, the right microphone essentially shows main rotor contributions only. Still, both signatures contain contributions from both rotors.

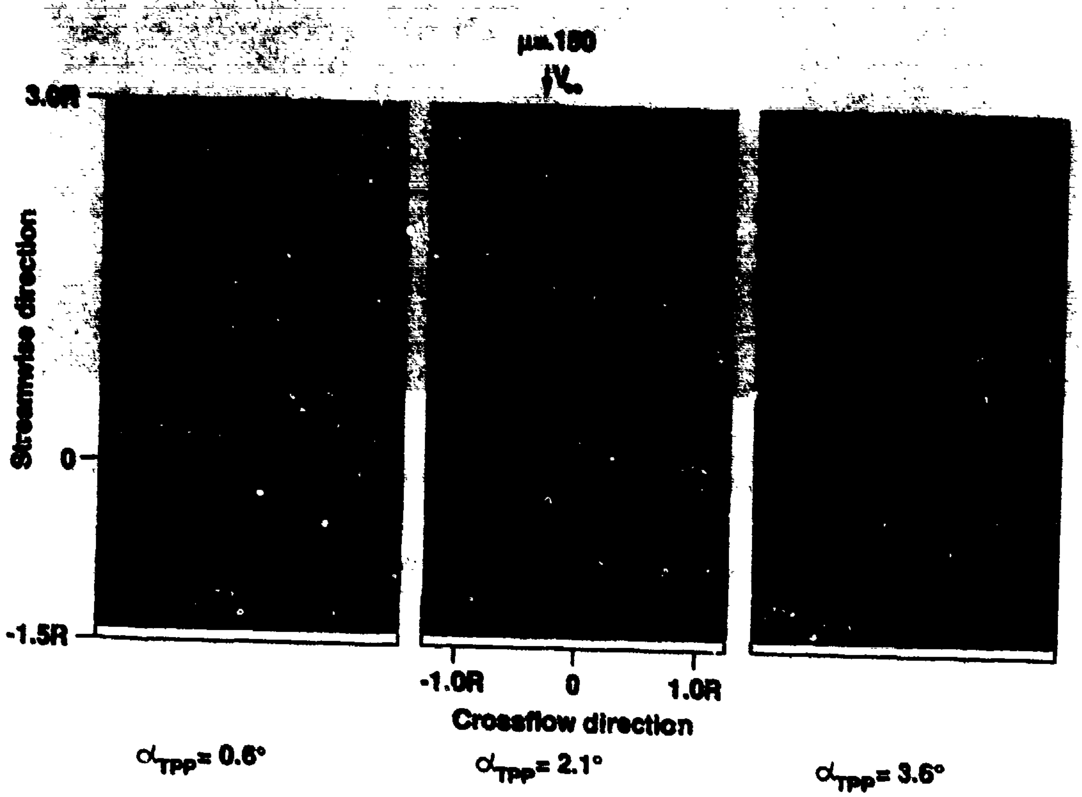


Fig. 4.43 Blade vortex interaction contour plots under main rotor system as shown in Fig. 4.42 a (from Ref. 60)

In analysing data it is possible to emphasise the acoustic signal of either the main rotor or of the tail rotor individually. Thus one can study the noise of each rotor by itself although the other rotor is operational. For example, with both rotors turning, the individual contribution to the total acoustic signal of the tail rotor (operating in the aerodynamic wake of the main rotor) may be "extracted".

Fig. 4.45 shows an example of this technique. The signature of the main rotor is largely suppressed by triggering the pressure time histories on some appropriate distinct tail-rotor-related time history feature (such as a pronounced peak). In this particular test set-up, however, the main and tail rotors were not mechanically connected (as is the case on a real helicopter). There was, therefore, no need to use the pressure time history for triggering. Rather could the tail rotor RPM be used directly for triggering.

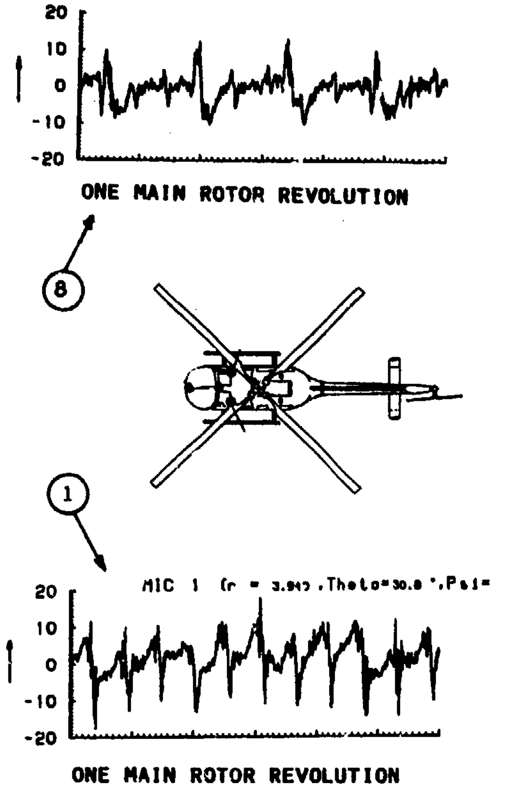


Fig. 4.44 Acoustic pressure time histories under main-rotor/tail-rotor

In contrast, the small variations in the distance between the test and the measuring aircraft and minor variations in rotational speeds in the analysis of actual flight test data, as described in Section 4.4, required a distinct acoustic signal-feature of the main rotor for triggering to extract the main rotor pressure time history from the "tail rotor contaminated" total signal.

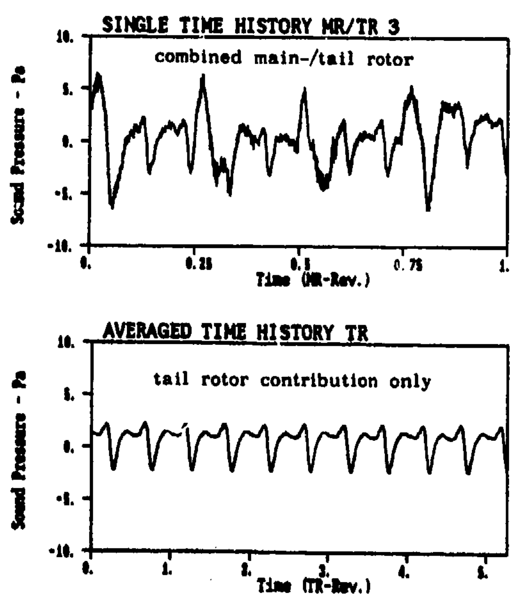


Fig. 4.45 Extraction of tail-rotor noise contribution only from a main-rotor/tail-rotor model experiment

The helicopter, which has been chosen as concluding example, illustrates well the fact that, even when there are obvious mechanical noise sources (e.g. vibration of blades, engine, gearbox), flow interaction can be a dominant sound generation mechanism for certain frequencies and directions. The aspects more difficult to study are the sound emitted by vortices as such as shed by blades, due to their flapping motion, bearing in mind that forward velocity also varies during a rotor revolution. The problem becomes more complicated still for the tail rotor, when it is in the wake of the main rotor, since 'chopping' of vorticity is another noise source.

5. CONCLUDING REMARKS

Aircraft noise certification has been practiced for well over one decade, encouraging the development of quieter aircraft and of noise abating flight operations. Much effort by the ICAO-Committee on Aviation Environmental Protection is currently put into "streemlining" the noise certification procedures. Simplification might ultimately be reflected in a new version of the ANNEX-16 document which would then be more readily understandible, still technically sound and would largely avoid any redundancy (being quite common in the present issue).

In the spirit of "streamlining" it would be desirable, for example, to develop a general noise certification procedure for all propeller-driven aeroplanes, encompassing essentially all types from the heavy commuter and transport-category aeroplane, to the smaller business- and recreational propeller-plane down to the powered glider and the ultralight-aeroplane. Within such a basic scheme certification complexity would decrease as the weight (cost) of an aircraft goes down. Hence heavy aeroplanes could be certificated with procedures 'take-off', 'level-overflight' (representing some sort of an "on-route noise" check) and 'approach' employing a fairly elaborate measurement chain and the "complicated" noise metric EPNL. Medium weight aeroplanes could be certificated through a 'take-off' and a 'level-overflight' procedure with the SEL as the noise metric measured through only one microphone, while light and ultralight aeroplanes would simply have to conduct a level overflight above one microphone with the L_A as the pertinent noise metric. Likewise, it should be possible to define a common noise-certification procedure for both subsonic and supersonic jet-aircraft, although noise-certificating the operational condition of supersonic cruise flight would probably be a difficult problem. By similar reasoning one could propose one basic noise certification scheme for helicopters that would pertain to both light and heavy ones. For the heavy helicopter one could adhere to the established procedure along the ANNEX Chapter 8, while for the light one a level overflight only, or a combination of a level overflight and approach test could be specified with the SEL obtained through one microphone only as the pertinent noise metric, thus considerably cutting cost.

It also seems important to consolidate the measuring-microphone height above ground within aircraft noise certification procedures. After all, the 1.2-meter height has been demonstrated to yield rather devastating results for propeller-driven aeroplanes for all noise evaluation metrics L_A, SEL and EPNL. Ground reflection effects may not be quite as critical for more broadband-type sounds as emitted by jet-aircraft. Still, for physical reasons the ground-proximity microphone would certainly offer less questionable data under most all testing circumstances. Employing ground-proximity microphones for all noise certification might be good practice.

The current multitude in the ANNEX-16 Appendices, one for each type of aircraft with very redundant information could certainly also be compressed into one Appendix only, providing all the necessary information for all types of aircraft and procedures in a non-redundant form.

What should be ultimately developed might be termed a "Grand Unified Noise Certification Scheme" for all aircraft, where all redundancy is strictly eliminated, and where the respective complexitiy of any noise certification procedure would be in concert with the basic cost of the aircraft concerned. The ICAO-Committee on Aviation Environmental Protection through its Working Groups and Technical Issues Subgroups is actively pursuing various avenues towards better aircraft noise certification Standards. Noise certification is a living process and as technical development proceeds in terms of both building better aircraft and more sophisticated instrumentation new aspects enter the philosophy and practice of noise certificating aircraft which need to be accounted for.

The development of a noise certification procedure for all aircraft with which everybody would be happy will probably never be realized. If as a consequence of noise certification there is success in developing technically and operationally significantly quieter aeroplanes - then every small step is worth the effort, such that, hopefully, at some future day aircraft noise would be no nuisance.

APPENDIX A: CALCULATION OF THE 'EFFECTIVE PERCEIVED NOISE LEVEL'

The flyover noise signature of an aircraft varies with time, both in intensity and spectral content. To account for the human subjective response to such a noise event, an appropriate single-number descriptor, the 'Effective Perceived Noise Level (EPNL)', has been developed.

To determine the EPNL of a flyover noise event, the data are processed to yield a succession of 1/3 octave band (1/3-o.b.) spectra in 0.5-second-increments during the time period of the entire flyover (Flow Chart, Fig. A-1). The important acoustic information to be processed is contained in a time span of 20 to 50 s during which the aircraft noise exceeds the ambient noise by at least 10 dB. Accordingly, 40 to 100 individual 1/3-o.b.-spectra are to be obtained. It should be kept in mind that within one half second an aircraft flies a distance of several tens of meters, substantially changing the characteristics of the noise signature as received on the ground.

A.1 Perceived Noise Level

Each 1/3-o.b. spectrum consists of 24 individual 1/3-octave-bands. Here band 1 has a center frequency of 50 Hz, band 2 of 63 Hz, band 3 of 80 Hz etc. up to band 24 with a center frequency of 10.000 Hz)*. Each of these band-levels is weighted by 'Contours of Perceived Noisiness', accounting for the pronounced sensitivity in the frequency range from 2000 to 5000 Hz, and the lesser - albeit absolute level-dependent - sensitivity at lower and higher frequencies within the audible range. Fig. A-2 shows the 'Perceived Noisiness Contours' of which each is designated with a noy-number.

These contours are then overlaid individually upon each of the (20 to 50) 1/3-o.b.-spectra to obtain 24 weighted band-levels, now termed 'Noy-values'. These Noy-values are called 'Perceived Noisiness'-values, or PN-values for short. Finally, all PN-values are added up, however still with some further 'weighting' such that the highest PN-value (not necessarily the highest band-level!) counts 85% and the sum of all others, including the highest, counts only 15%, i.e.

$$N(k) = 0.85\ n(k) + 0.15 \sum_{i=1}^{24} n(i,k) \qquad \text{(A1)}$$

where N(k) is the 'Total Perceived Noisiness', n(k) is the largest of the 24 PN-values of n(i,k). Here i is the band-number (1,2,3, ... 24) within the spectrum and k denotes the particular spectrum of the flyover.

The 'Total Perceived Noisiness' is then converted back into a 'Perceived Noise Level, PNL' by

$$PNL(k) = 40 + 33.2 \log N(k) \qquad \text{(A2)}$$

Having thus obtained one, and one only, PNL-value for each spectrum, one may now already go ahead and plot a flyover-history of PNL vs time, unless the original spectra contained pronounced discrete-frequency, tonal components. In this case each spectrum must first be corrected for 'spectral irregularities' to obtain the 'tone corrected Perceived Noise Level, PNLT', by means of a tone correction.

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* The agreed upon sequence of 1/3-octave band center frequencies is: ... 100 Hz, 125 Hz, 160 Hz, 200 Hz, 250 Hz, 315 Hz, 400 Hz, 500 Hz, 630 Hz, 800 Hz, 1000 Hz, 1250 Hz ...., etc

A.2 Tone Correction

Tone correction is a rather elaborate process and shall be explained using the Flow Chart shown in Fig. A-3. First, a listing is made, individually for each spectrum, of the sound-pressure levels L_p in each successive band, with the exception of the two lowest bands, 50 Hz and 63 Hz (Column A). The listing thus starts with band 3 (i.e. 80 Hz).

Let us consider the first six bands 3 to 8, corresponding to frequencies 80, 100, 125, 160, 200 and 250 Hz. The difference in sound pressure level from one band to the next (positive or negative) is listed in Column B. These differences are termed 'slopes'. Column C then lists the absolute changes in slopes. Now, if any value in Column C is greater than 5, then back in Column B the value one half notch down will be encircled, i.e. in the example the values -7 and +4, since both 8 and 11 are larger than 5 in Column C.

Next, one of two criteria are applied:

(1) if in Column B the encircled value is positive and greater than the value directly above it, then in Column A the value one half notch down will be encircled; in our example +4 is both positive and greater than -7, therefore 80 is encircled.

(2) if in Column B the encircled value is zero or negative, and the previous value is positive, then in Column A the value one half notch up is encircled. In our example -7 is negative and the previous value +1 is positive; therefore 83 is encircled.

Next the sound pressure levels in Column A are adjusted as follows: Each encircled L_p-value is replaced by the arithmetic average of the preceeding and the following L_p-values. Thus, 83 becomes replaced by $|(82+76)/2| = 79$, and 80 by $|(76-80)/2| = 78$. The adjusted listing appears in Column A_{adj}.

Thereafter, new level-differences are computed and listed in Column D, whereby the level-difference between an imaginary band No.2 and band No.3 is set, by convention, equal to that between bands 3 and 4, in our example +2. 'Average slopes' are now computed by taking, respectively, three successive slopes and calculating the arithmetic average, i.e.

(A3) $$\text{average slope} = 1/3\ (\text{slope } 1 + \text{slope } 2 + \text{slope } 3)$$

and listed in Column E.

The final adjusted levels (to be listed in Column F) are obtained as follows: Band 3 remains unchanged as in Column A. Band 4 level is taken as the sum of the Band 3 level and the average slope, as listed in Column E, i.e. 80+1/3 = 80 1/3. Correspondingly, Band 5 level is taken as Band 4 level plus the next average slope, i.e. 80 1/3 - 1 1/3 = 79, etc.

In the end the level differences between the original sound pressure level (Column A) and the final adjusted level (Column F) are listed in Column G, but only those which are greater than zero. The numerical values in Column G are then converted into the tone-correction factors, C(k), as follows:

If the 1/3-o.b. under consideration has a center frequency of (and including) 500 Hz up to 5000 Hz, the Column G values are divided by 3 to obtain C(k); if however the center frequency is below 500 Hz and above 5000 Hz, values are divided by 6 to obtain C(k). Only the largest of the tone correction factors is ultimately added to the 'Perceived Noise Level', such that the 'Tone-corrected Perceived Noise Level, PNLT,' becomes

(A4) $$PNLT(k) = PNL(k) + C(k)$$

with C(k) as the largest tone correction factor listed in Column H. In the example, the tone correction factor is rather small since it occurred in band 5 (125 Hz). If the same 'G-value' had occurred at band 14 (1000 Hz), C(k) would become 1 1/3 dB. The numerical value of the largest permissible tone correction factor is 6 2/3 dB. For each of the 1/3-o.b.-spectra occurring in 1/2-second increments during a flyover one may determine one PNLT(k) value. Thus, a PNLT-time history for the flyover under consideration can be plotted, where - at some point in time - a maximum PNLT-value occurs. This maximum value, termed PNLTM, now enters the further computational procedures.

A.3 Duration Correction

During a typical flyover, aircraft noise is first heard when it can be distinguished from the background noise and until it eventually submerges again into the ambient. The human subjective response depends to a large extent on the time-duration of the flyover-noise signature, such that a brief audible time-history might be less disturbing than one that extends for a long period of time.

Thus, the 'time duration' (defined as the time span for which the PNLT values exceed the maximum PNLT value (i.e. PNLTM) minus 10 dB (Fig. A-4)) also enters the EPNL-computation. The ensuing time-duration factor, D, - also sloppily referred to as "10-dB-down-time" - is defined as follows:

(A5)
$$D = 10 \log \left[\frac{1}{T} \int_{t_1}^{t_2} \text{antilog} \frac{PNLT}{10} \, dt \right] - PNLTM.$$

Here, T is a normalizing factor, and, by convention, taken as 10 seconds, and t_1 and t_2, respectively, are the points in time when PNLT first exceeds the value (PNLTM-10) and after it remains less than the value (PNLTM-10).

Since there does not exist a mathematical expression (function) for the PNLT-flyover time history, but rather a number of individual time-sequential PNLT-values one rather uses a summation instead of an integral, i.e.

(A6)
$$D = 10 \log \left[\frac{1}{T} \sum_{k=0}^{d/\Delta t} \Delta t \ \text{antilog} \left(\frac{PNLT(k)}{10} \right) \right] - PNLTM \quad ,$$

where k denotes the k-th data point (at 1/2 s intervals) during the flyover, Delta t is the time-sequential interval (1/2 s), d is the time duration during which PNLT exceeds (PNLTM-10).

Taking T = 10 s and Delta t = 0.5 s, Eq.(A6) reduces to

(A7)
$$D = 10 \log \left[\sum_{k=0}^{2d} \text{antilog} \left(\frac{PNLT(k)}{10} \right) \right] - PNLTM - 13 \ .$$

If the flyover was a fast one, the PNLT-history might look as in Fig. A-5a; if it was a slow as in Fig. A-5b. In both cases the maximum value is identical and equal to 100 PNLTMdB. In the first case, however, fewer PNLT-values are added up (namely only k = 11), while in the second case many more values (k = 31) contribute. In the example the duration correction factor is -9 dB for the fast flyover and -5.9 dB for the slow flyover, i.e. 4 dB larger.

The duration factor as such is of course independent of the maximum PNLT-value, and in fact, the PNLTM does not explicitly enter the final EPN-level since it cancels when introducing the duration correction.

A.4 Final EPNL-value

The Effective Perceived Noise Level (including tone and duration correction) now becomes

(A8) $$EPNL = PNLTM + D$$

where D usually is a negative number. From the definition of D, which includes a subtraction of PNLTM one finds

(A9) $$EPNL = 10 \log \left(\frac{1}{T} \int_{t_1}^{t_2} 10^{PNLT\ (k)/10}\ dt \right)$$

or rather

(A10) $$EPNL = 10 \log \left(\sum_{k=0}^{2d} 10^{\ PNLT\ (k)} \right) - 13 \quad .$$

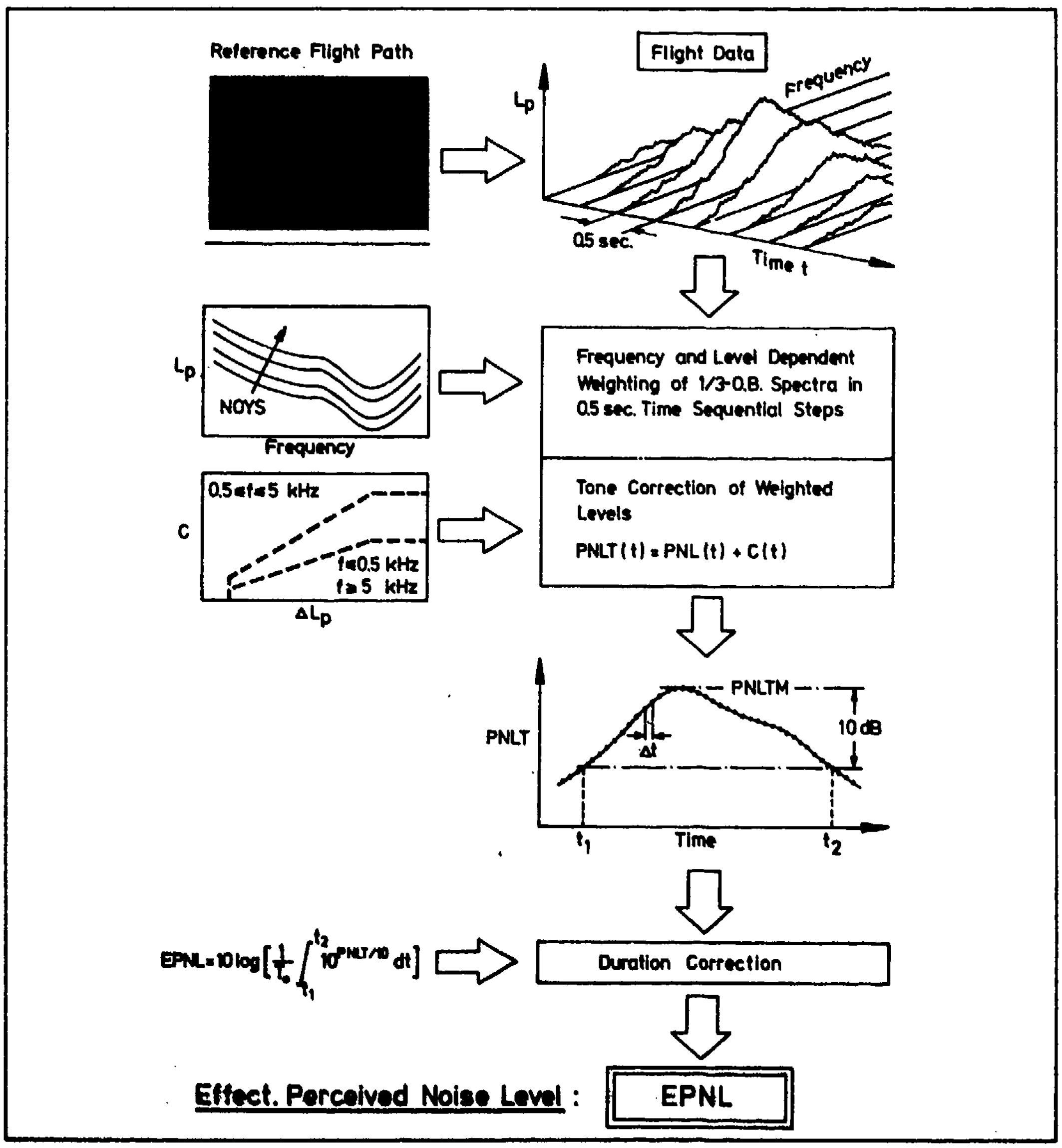


Fig. A-1 Flow chart to determine flyover noise EPNL-values

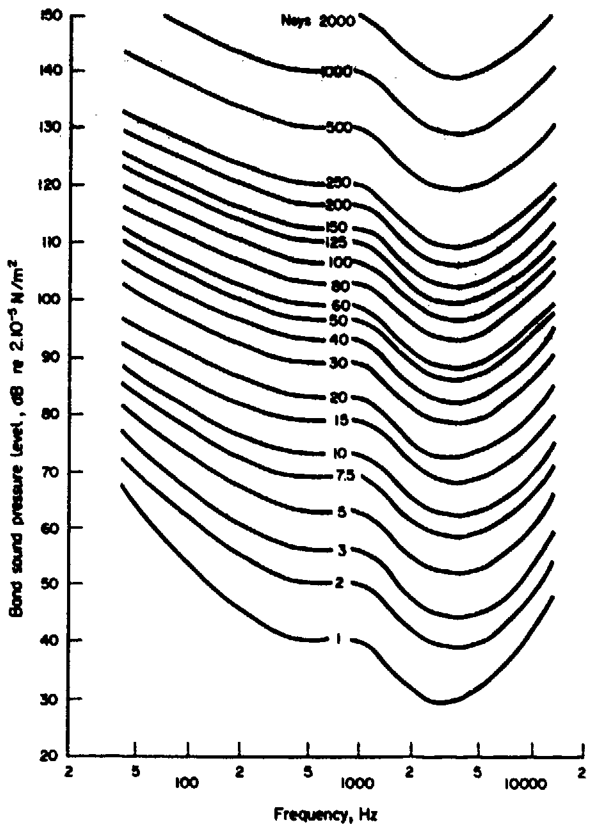


Fig. A-2 Contours of Perceived Noisiness

Column		A	B	C	$A_{adj.}$	D	E	F	G	H
Band #	1/3-Ob. Center-Frequency Hz	L_p dB	Slope	Slope-change	L_p dB	Slope	ΔL dB	L_p dB	ΔL dB	C(k) dB
3	80	80			80	+2	$+\frac{1}{3}$	⊕-80	—	
4	100	82	+2	1	82	+2	$-1\frac{1}{3}$	⊕-80 $\frac{1}{3}$	$1\frac{2}{3}$	0.28
5	125	(83)	+1	8	79	-3	$-1\frac{1}{3}$	⊕-79	4	(0.67)
6	160	76	(-7)	11	76	-3	$+\frac{1}{3}$	⊕-77 $\frac{2}{3}$	—	
7	200	(80)	(+4)	4	78	+2		78	2	0.33
8	250	80	0		80	+2				

Fig. A-3 Flow chart: tone correction for EPNL computation

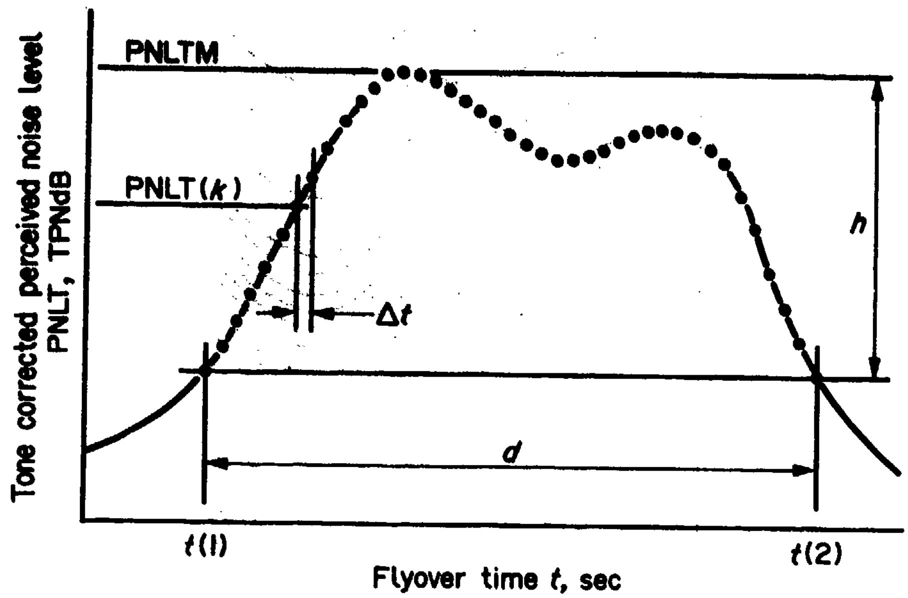


Fig. A-4 Definition of time duration within PNLT time history plots

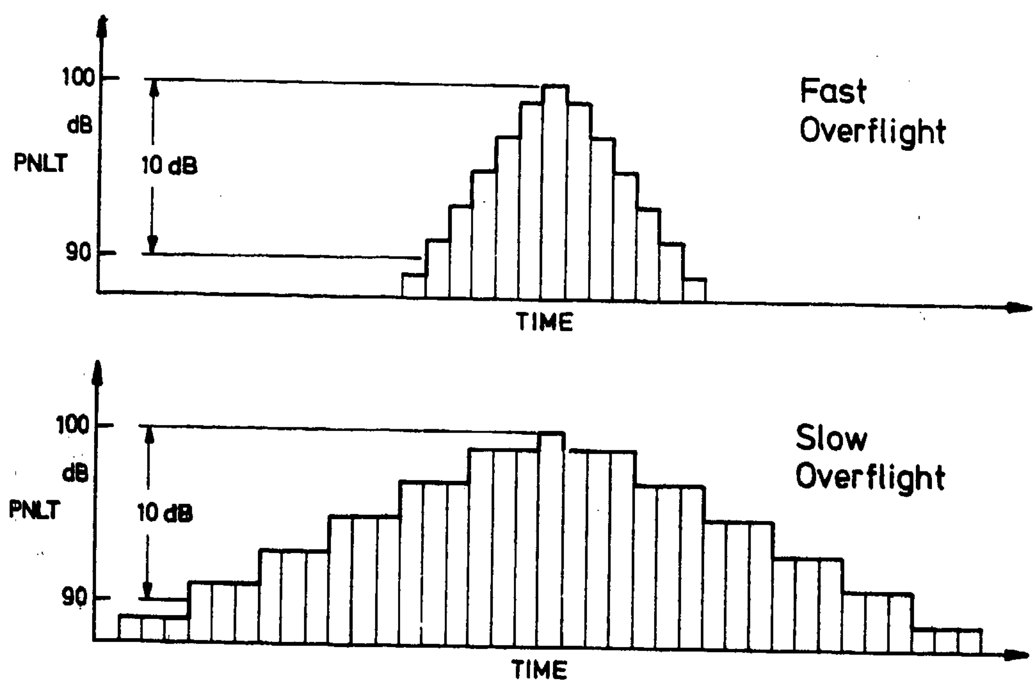


Fig. A-5 Idealised PNLT flyover time histories

APPENDIX B: ACOUSTICAL CHANGE EVALUATION AND PRECISION OF FLYOVER NOISE MEASUREMENTS

If an aircraft does not pass a noise certification test, "acoustical changes" (employing, e.g. a less noisy propeller or an improved muffler) are necessary to lower its noise emission. The question arises, whether the acoustic test procedure, as prescribed for certification, is a suitable method for the purpose and whether the attainable "statistical precision" suffices to evaluate the success of any such acoustical change. There is often a tendency to take measured noise levels at their "face-value", neglecting the measurement uncertainty that is inherent in the statistical nature of noise data obtained from an aircraft in flight. The following discussion is largely based on |61 and 62|.

To ascertain the validity of noise measurements, certification regulations require that the arithmetic mean of at least 4 (or 6) flyover noise levels shall be produced. In any case, however, the "final" sample size must be large enough to establish a 90% confidence limit not exceeding +/- 1.5 dB (See AGARDograph-Appendix E); hence it might be necessary to obtain test data through more than 4 (or 6) flyovers. It is obvious that the data scatter may become quite large as long as the standard error of the mean of noise levels s_x does not exceed an asymptotical value of 0.9 dB with increasing number of flyovers (Fig. B-1). Practice has shown, that data, which comply with this requirement, are not difficult to obtain for propeller-driven aircraft. If in the process of comparing two or more aircraft with two or more empirical mean noise levels (with their individual variances), however, then this validation procedure does not suffice!

B.1 Gaussian Data-Distribution and Homogeneity of Variance

To assess significant changes (in terms of mean level differences) it is imperative to take the statistical nature of the data into account. Within the ANNEX regulations the noise level data are treated as if they formed a normal (Gaussian) distribution in the "dB-space". If this was indeed true and if, in addition, both variances s^2_x of the respective samples were of the same magnitude, then t-statistics for two means could be readily applied to test for significant differences $\text{Delta}_{0.05}$, corresponding to an error probability of $\alpha = 0.05$. (It is customary to use a $\text{Delta}_{0.05}$ for "significance-testing").

The following is to illustrate the procedure. Fig. B-2 shows two examples of flight noise data obtained under realistic test conditions. In both cases aircraft were tested before and after some acoustical change had been implemented (such as the replacement of a "noisy" with a "quiet" propeller). 'Aircraft A' was tested 4 times in one configuration, then 4 times in the other configuration, providing, respectively, 2 times 4 levels, with 2 resulting mean-levels. It turned out that the variations in level from one test flyover to the next within a test series of 4 were quite small; moreover, the difference of the 2 mean levels was also quite small, namely 0.5 dB.

Some other 'Aircraft B' was also tested 4 times in one configuration and then 4 times in another configuration, again providing 2 times 4 levels with 2 mean levels. Here it turned out that the level variations from one test flight to the next within one test series of 4 were quite large; moreover the difference in the mean levels was also quite large, namely 2.0 dB.

In the case of 'Aircraft A' one might be tempted to say: "Ah well, the difference in the mean levels for the aircraft before and after the change is kind of small, isn't it. Surely, changing the propeller has not gotten us anywhere!". - Enter 'Aircraft B': Here one might say: "Gee, look at the difference after we changed the propeller. Its a good solid 2.0 dB. Surely, this time the change has brought about quite some improvement!"

Such "intuitive" statements are however not only dangerous, they can be outrightly wrong! One must consider the statistics of the data and determine the minimum necessary level-difference for significance. A level difference of 0.5 dB can be statistically significant, another of 2.0 dB can be statistically insignificant.

Test series 1 and 2 of 'Aircraft A' showed very small standard deviations (both approximately $s_x = 0.23$ dB), series 1 and 2 of 'Aircraft B' showed large standard deviations (both approximately $s_x = 1.33$ dB). The reproduced tests for 'Aircraft A' indicated the mean level to be higher by 0.5 dB, for 'Aircraft B' to be lower by 2.0 dB. The basic question then arises, whether these differences are statistically significant or not.

Under the simplifying assumptions that in each test series the sample size N_f was the same (namely 4), that furthermore the variances s^2_x were identical (namely 0.23^2 in case 'A', and 1.33^2 in case 'B') one could simplify the mathematical expression for ($\mathrm{Delta}_{0.05}$)-significance testing to:

$$\mathrm{Delta}_{0.05} > t_{0.05;2N_f-2}\sqrt{\frac{2\,s^2}{N_f}}$$

where $\mathrm{Delta}_{0.05}$ is the minimum level difference for significance with an error probability α of 0.05 or 5%, and $t_{0.05;2N_f-2}$ is the 'student factor' (see Table E-1 in AGARDograph-Appendix E). This latter factor, for $N_f = 4$ would assume a value of 2.477. Accordingly, for the example used, $\mathrm{Delta}_{0.05}$ would be 0.4 dB in case 'A'; thus the test result would indicate 'significance' of the mean-level difference of 0.5 dB. In case 'B' $\mathrm{Delta}_{0.05}$ would be 2.3 dB; hence the observed mean-level difference of 2.0 dB (being less than the minimum required one of 2.3 dB) would render the difference not significant in a statistical sense, although the absolute level difference is larger than for 'Aircraft A'.

For convenience, Fig. B-3 shows the relationship of standard deviation and the borderline "significant" level difference within which - for a given standard deviation - a level difference would be statistically significant under the above made assumptions of equal test numbers N_f and "identical" standard deviations for both test series. The examples shown in Fig. B-2 are indicated.

B.2 Non-Gaussian Data Distribution and Inhomogeneity of Variance

Usually one cannot assume a normal distribution of data and variances are usually not homogeneous. Frequently, even data within a single sample stem from two different basic ensembles (e.g. those obtained for the upwind and downwind legs of test flights).

Practice has shown that the 90% confidence level ($\alpha = 0.10$) derived within the certification procedure really only provides a measure of 'repeatability' (or "closeness in agreement") of the noise data obtained within one test-series by one observer with the same instrumentation in one place and within a comparatively short time span under fairly identical meteorological condition.

A newly produced data sample of comparable size, even from the same test-aircraft by the same observer and instrumentation but at some other time or location would probably produce a mean noise level with a different variance. In this case, the 'reproducibility' of both sets of data must be determined. Only when making use of both the 'repeatability' and the 'reproducibility' could one derive more general "critical differences" (such as, e.g. a more general confidence limit).

To illustrate these considerations, flyover noise data from 8 test aeroplanes are used. Although the available data contains a substantial amount of information, statistical evaluation has its limitation due to the still rather small individual sample size, both in terms of the 'replication rate' (of 4 to 6 flyovers within a test series) and of the 'repetitions rate' (repetition at different times and locations) of typically two or three in the examples shown. The particular difficulty lies in the identification of possible 'outliers' and 'irregularities' and in establishing the homogeneity of variances. Checks whether a normal (i.e. "Gaussian") distribution could be assumed showed that this was not the case for the A-weighted levels, L_{pAS}, that were considered here.

In order to derive the subject 'Precision Data', both a "Within-test-series Variance" σ_r^2 and a "Between-test-series Variance" σ_T^2 was determined. σ_r^2 was usually evaluated from a total of 4, sometimes 6, flyovers conducted within a short time period, whereby the data had been acquired by two independent measurement groups. σ_T^2 in turn was evaluated from series of 2 or 3 test-campaigns (each series resulting in one σ_r^2 variance); each test-campaign in itself was considered a new and independent test. By combining the "Within-test-series Variances" and the "Between-test-series Variances" one can now go ahead and define a "Reproducibility Variance"

$$\sigma_R^2 = \sigma_r^2 + \sigma_T^2$$

for a test series reproduced at a different time and/or location but with exactly the same aircraft as well as observer and equipment.

The subject "Precision Data" are then defined as

$$\text{Repeatability} \quad r = 2.83\,\sigma_r$$
$$\text{Reproducibility} \quad R = 2.83\,\sigma_R$$

where the factor 2.83 is a rounded off $\sqrt{2}\,t_{\infty;0.05}$. Here $\sqrt{2}$ is included since differences between two measurements are described; $t_{\infty;0.05}$ is Student's factor (See TABLE E-1 of this AGARDograph) for a sample of infinite size and a probability-level of 95%. r and R can be considered as bounds of normal-distributed variables. Most differences, occuring when measurements are repeated and reproduced, will therefore be either of equal size or smaller.

From the Precision Data r and R critical differences with a particular probability level p - usually 95% - can be derived. One such derived quantity is the general confidence level,

$$u_R = (1/\sqrt{2})\cdot\sqrt{R^2 - r^2(1-1/n)}$$

where n is the number of multiple repetitions of the measurements.

Experimental results from a comparative study are shown in Fig. B-4. In general, 'repeatabilities' r of between 1 and 2 dB were found with the exception of two aircraft, a powered glider (aircraft A) and a turboprop aeroplane (aircraft H), resp., for which the subject evaluation procedure was not particularily suited. Larger values of repeatability of up to 3 dB indicate an inappropriate test procedure, such as accelerated flights (aircraft A) or strong effects of atmospheric turbulence (aircraft H). All other aircraft indicate close identity within the multiple-determined repeated tests. Homogeneity of variances within such multiple-determined tests could always be demonstrated; inhomogeneity on the other hand was a clear indication of errors.

Reproducibility was found to range from 2 to 3 dB, and sometimes to reach values greater than 4 dB. The actual values show rather conclusively, that there is a risk in comparing noise levels of exactly the same aircraft after test conditions have changed in a non-controllable way.

The combination of the precision data into a general 'confidence limit' u_R shows values of 1 to 2 dB (Fig. B-5), which is much greater than the typical average confidence level of a single test series. Indeed, these rather large values cannot be reduced much by replication. (The results, as shown in Fig. B-5 refer to a probability-level of 95%, suitable for estimates of the significance of differences).

One must warn therefore not to take noise data from certification tests as basic material to ascertain acoustical changes of only a few deziBels in a statistically significant manner. The determination of the precision data 'repeatability' and 'reproducibility' and perhaps of more a general confidence limit should provide a better indication of how reliable such comparative measurements really are.

Noise measurements for purposes other than certification should therefore be planned to render statistically significant proofs. One could for example consider a series of, say, up to 8 flights of one basic ensemble measured simultaneously through two independent data channels. Precision however could best be improved if 'paired' or 'matched' tests were carried out; these have a better test power or selectivity. Above all, it will often be less costly to fly two aircraft simultaneously than to perform consecutive tests with one aircraft resulting in questionable test data significance.

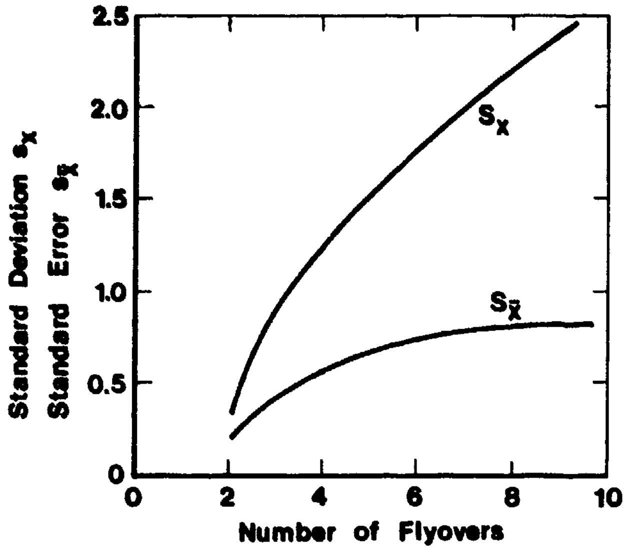


Fig. B-1 Maximum permissible standard deviation s_x and resulting standard error of the mean $s_{\bar{x}}$ as function of the number of flyovers for a 90% confidence limit not exceeding +/-1.5 dB.

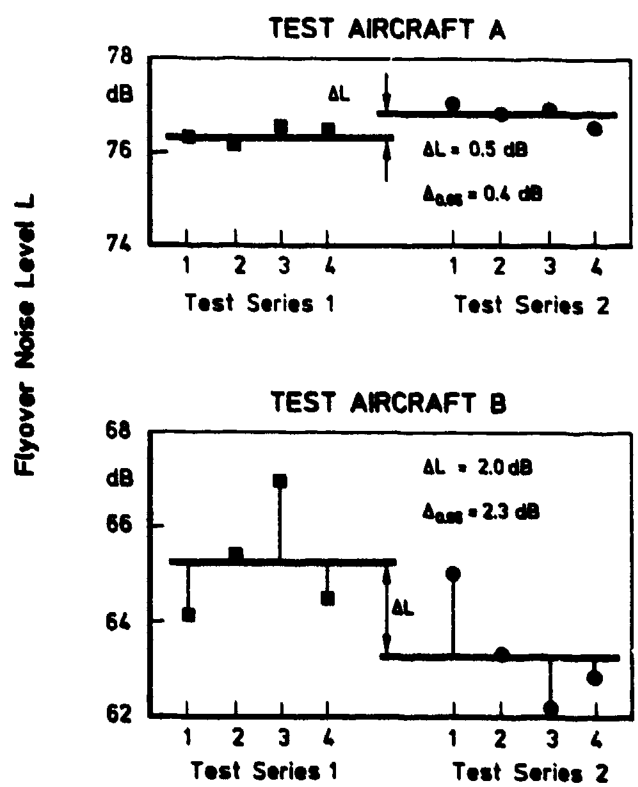


Fig. B-2 Typical propeller aircraft flyover noise levels with (a) very small and (b) very large standard deviation and respective minimum required mean level differences for significance $Delta_{0.05}$

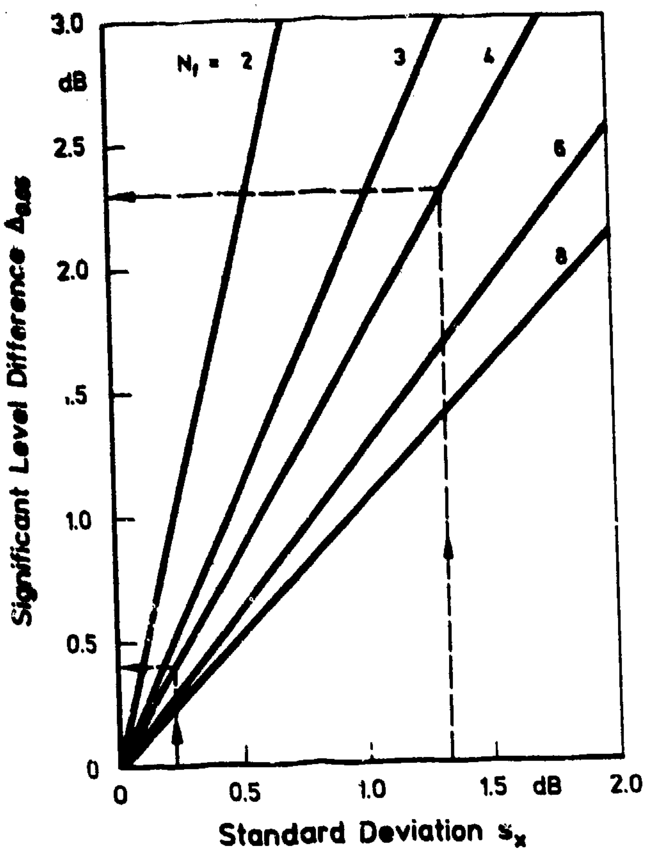


Fig. B-3

Areas of significant level differences $Delta_{0.05}$ for error probability of 5% as function of standard deviation s_x vs. number of flyovers N_f

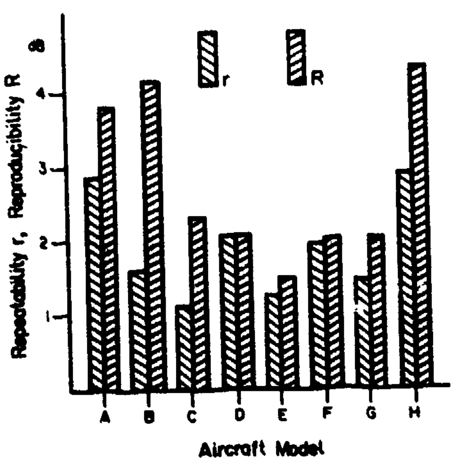
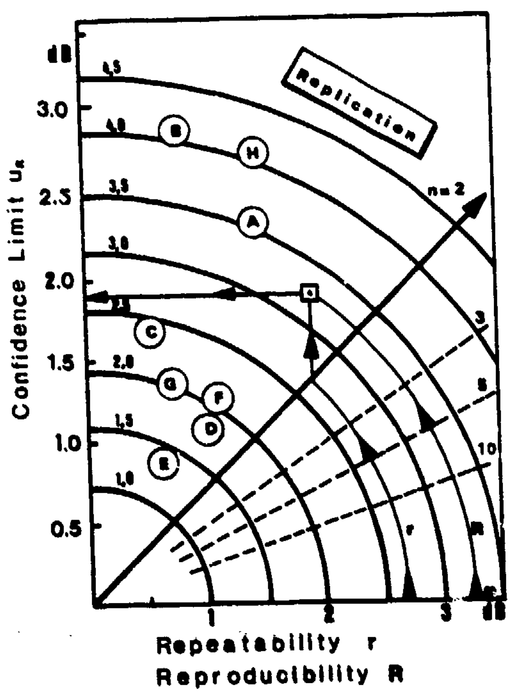


Fig. B-4 Precision data 'Repeatability r' and 'Reproducibility R' for 8 propeller-driven aeroplanes (A to H)

Fig. B-5

Confidence limits based on 'Repeatability r' from replicated tests and 'Reproducibility R' for 8 propeller-driven aeroplanes (A to H)



APPENDIX C: NOISE CERTIFICATION COMPARISON ACCORDING TO AIRCRAFT TYPES AND CATEGORIES

The structure of each Chapter and Appendix of ANNEX 16 generally follows the same pattern. Therefore, in order to make individual differences in the treatment of the various aircraft types and categories more obvious, this AGARDograph-Appendix lists each test aspect in terms of 'Applicability', 'Noise Evaluation Measure', 'Noise Reference Measurement Point(s)', 'Maximum Noise Level(s)', 'Trade-offs', 'Noise Certification Reference Procedure: Atmospheric Conditions', 'Noise Certification Reference Procedure: Engine Power and Flight Speed', 'Test Environment', 'Adjustment to Test Results', and 'Test Result Validity'. The specifications will individually refer to

(1) **Propeller-driven Aeroplanes over 9000 kg** with Airworthiness Certificate Application ("ACA") on/after 17 Nov. 1988 (ANNEX 16 Chapter 3 / Appendix 2)

(2) **Subsonic Jet Aeroplanes** with Airworthiness Certificate Application ("ACA") on/after 6 Oct. 1977 (ANNEX 16 Chapter 3 / Appendix 2)

(3) **Propeller-driven Aeroplanes not exceeding 9000 kg** with Airworthiness Certificate Application ("ACA") before 17 Nov. 1988 (ANNEX 16 Chapter 6 / Appendix 3)

(4) **Propeller-driven Aeroplanes not exceeding 9000 kg** with Airworthiness Certificate Application ("ACA") on/after 17 Nov. 1988 (ANNEX 16 Chapter 10 / Appendix 6)

(5) **Helicopters** with Airworthiness Certificate Application ("ACA") on/after 1 Jan. 1985 or with Application for change of type design on/after 17 Nov. 1988 (ANNEX 16 Chapter 8 / Appendix 4)

APPLICABILITY

(1) **Propeller-driven Aeroplanes over 9000 kg**

- Propeller-driven aeroplanes including their derived versions

(2) **Subsonic Jet Aeroplanes**

- Subsonic jet aeroplanes including their derived versions (other than those which require a runway length of 610 m or less at MCTOM

(3) **Propeller-driven Aeroplanes not exceeding 9000 kg** (ACA before 17 Nov. 1988)

- Propeller-driven aeroplanes - other than aerobatic, fire-fighting, and agricultural - with a certificated take-off mass not exceeding 9000 kg (except for derived versions with airworthiness application on/after 17 Nov. 1988, for which Chapter 10 applies)

(4) **Propeller-driven Aeroplanes not exceeding 9000 kg** (ACA on/after 17 Nov. 1988)

- propeller driven aeroplanes and their derived versions- other than aerobatic, fire-fighting, and agricultural - with a MCTOM not exceeding 9000 kg

(5) **Helicopters**

- Helicopters - other than those designed for external load carrying, fire-fighting and agricultural purposes

NOISE EVALUATION MEASURE

(1) **Propeller-driven Aeroplanes over 9000 kg**

- Effective Perceived Noise Level (EPNL)

(2) **Subsonic Jet Aeroplanes**

- Effective Perceived Noise Level (EPNL)

(3) **Propeller-driven Aeroplanes not exceeding 9000 kg** (ACA before 17 Nov. 1988)

- maximum A-weighted flyover noise level ($L_{pA,max}$)

(4) **Propeller-driven Aeroplanes not exceeding 9000 kg** (ACA on/after 17 Nov. 1988)

- maximum A-weighted flyover noise level ($L_{pA,max}$)

(5) **Helicopters**

- Effective Perceived Noise Level (EPNL)

NOISE REFERENCE MEASUREMENT POINT(S)

(1) **Propeller-driven Aeroplanes over 9000 kg**

- Take-off Test Sideline: several points parallel and 450 m from the runway center line
- Take-off Test Flyover: point on extended runway center line 6500 m past start of roll
- Approach Test: point 120 m below the 3° descent path

(2) **Subsonic Jet Aeroplanes**

- Take-off Test Sideline: several points parallel and 450 m from the runway center line
- Take-off Test Flyover: point on extended runway center line 6500 m past start of roll
- Approach Test: point 120 m below the 3° descent path

(3) **Propeller-driven Aeroplanes not exceeding 9000 kg** (ACA before 17 Nov. 1988)

- Level Flyover Test: Point 300 m vertically below flight path

(4) **Propeller-driven Aeroplanes not exceeding 9000 kg** (ACA on/after 17 Nov. 1988)

- Point on runway center line 2500 m past start of roll

(5) **Helicopters**

- Take-off Test: Point vertically below flight path and 500 m horizontally past the point where transition to climbing flight (rotation point) is initiated; two other points symmetrically disposed at 150 m on both sides to the center point
- Level Flyover Test: Point 150 m vertically below the flight path; two other lateral points as above
- Approach Test: Point 120 m vertically below the flight path for a 6°-approach-path; two other lateral points as above

MAXIMUM NOISE LEVELS (mass dependent)

(1) **Propeller-driven Aeroplanes over 9000 kg**

- Take-off Test Sideline: 96 - 103 EPNdB
- Take-off Test Flyover: 89 - 106 EPNdB
- Approach Test: 98 - 105 EPNdB

(2) **Subsonic Jet Aeroplanes**

Take-off Test Sideline: 94 - 103 EPNdB

Take-off Test Flyover:
- 2-engine aircraft: 89 - 101 EPNdB
- 3-engine aircraft: 89 - 104 EPNdB
- 4-engine aircraft: 89 - 106 EPNdB

Approach Test: 98 - 105 EPNdB

(3) **Propeller-driven Aeroplanes not exceeding 9000 kg** (ACA before 17 Nov. 1988)

Level Flyover Test: 68 - 80 dB(A)

(4) **Propeller-driven Aeroplanes not exceeding 9000 kg** (ACA on/after 17 Nov. 1988)

Take-off Test: 76 - 88 dB(A)

(5) **Helicopters**

(3 microphone average)

Take-off Test:	86 - 106 EPNdB
Level Flyover Test:	85 - 105 EPNdB
Approach Test:	87 - 107 EPNdB

TRADE-OFFS

(1) **Propeller-driven Aeroplanes over 9000 kg**

- o Sum of excesses not greater than 3 EPNdB
- o Any single point excess not greater than 2 EPNdB
- o Any excess offset by reduction(s) at other point(s)

(2) **Subsonic Jet Aeroplanes**

- o Sum of excesses not greater than 3 EPNdB
- o Any single point excess not greater than 2 EPNdB
- o Any excess offset by reduction(s) at other point(s)

(3) **Propeller-driven Aeroplanes not exceeding 9000 kg** (ACA before 17 Nov. 1988)

- o not applicable

(4) **Propeller-driven Aeroplanes not exceeding 9000 kg** (ACA on/after 17 Nov. 1988)

- o not applicable

(5) **Helicopters**

- o Sum of excesses not greater than 4 EPNdB
- o Any single point excess not greater than 3 EPNdB
- o Any excess offset by reduction(s) at other point(s)

NOISE CERTIFICATION REFERENCE PROCEDURE: ATMOSPHERIC CONDITIONS

(1) **Propeller-driven Aeroplanes over 9000 kg**

- o Sea level atmospheric pressure 1013.25 hPa
- o Ambient Temperature 25 °C (ISA + 10 °C); 15 °C if approved by Certification Authority
- o Relative Humidity 70%
- o Zero Wind

(2) **Subsonic Jet Aeroplanes**

- o Sea level atmospheric pressure 1013.25 hPa
- o Ambient Temperature 25 °C (ISA + 10 °C); 15 °C if approved by Certification Authority
- o Relative Humidity 70%
- o Zero Wind

(3) **Propeller-driven Aeroplanes not exceeding 9000 kg** (ACA before 17 Nov. 1988)

- o Sea level atmospheric pressure 1013.25 hPa
- o Ambient temperature 25 °C (ISA + 10 °C)

(4) **Propeller-driven Aeroplanes not exceeding 9000 kg** (ACA on/after 17 Nov. 1988)

- o Sea level atmospheric pressure 1013.25 hPa
- o Ambient Temperature 15 °C (ISA)
- o Relative Humidity 70%
- o Zero Wind

(5) **Helicopters**

- o Sea level atmospheric pressure 1013.25 hPa
- o Ambient Temperature 25 °C (ISA + 10 °C); 15 °C if approved by Certification Authority
- o Relative Humidity 70%
- o Zero Wind

NOISE CERTIFICATION REFERENCE PROCEDURE: ENGINE POWER AND FLIGHT SPEED

(1) **Propeller-driven Aeroplanes over 9000 kg**

Take-off: with take-off power until reaching a flight height of

- o 300 m (aeroplane with 2 engines)
- o 260 m (aeroplane with 3 engines)
- o 210 m (aeroplane with 4 engines)

Therafter whichever power is greater to maintain a 4%-climb-gradient or a one-engine out level flight; all engine operating climb speed of at least V_2 + 19 km/h (where V_2 is the safe take-off speed) to be attained right after lift off; landing gears may be retracted as soon as practical, the mass must correspond to the take-off mass

Approach: to be made at a speed no less than 1.3 V_s + 19 km/h (where V_s is the stall-speed) and stabilized power. Landing gears must be down, mass to correspond to maximum landing mass.

(2) **Subsonic Jet Aeroplanes**

Take-off: with take-off power until reaching a flight height of

- o 300 m (aeroplane with 2 engines)
- o 260 m (aeroplane with 3 engines)
- o 210 m (aeroplane with 4 engines)

Therafter whichever power is greater to maintain a 4%-climb-gradient or a one-engine out level flight; all engine operating climb speed not to exceed V_2 + 37 km/h (where V_2 is the safe take-off speed) to be attained right after lift off; landing gears may be retracted as soon as practical, the mass must correspond to the take-off mass

Approach: to be made at a speed no less than 1.3 V_s + 19 km/h (where V_s is the stall-speed) and stabilized power. Landing gears must be down, mass be the maximum landing mass.

(3) **Propeller-driven Aeroplanes not exceeding 9000 kg** (ACA before 17 Nov. 1988)

Highest engine power in the normal operating range at stabilized airspeed and in cruise configuration

(4) **Propeller-driven Aeroplanes not exceeding 9000 kg** (ACA on/after 17 Nov. 1988)

Take-off with maximum take-off mass and take-off power until a height above the runway of 15 m has been reached, thereafter gears up and flaps in climb configuration with maximum power and propeller-RPM at a speed corresponding to the best rate-of-climb speed

(5) **Helicopters**

Take-off: with maximum take-off mass and take-off power at the best rate of climb along a path starting from a point located 500 m ahead of the reference point, and 20 m above the ground maintaining the best rate-of-climb speed during the subsequent climb at rotor-speed stabilized at the maximum normal operating RPM.

Flyover: with maximum take-off mass and stabilized in level flight at the greater speed of either 0.45 V_H + 120 km/h or 0.45 V_{NE} + 120 km/h, again with a rotor-speed stabilized at the maxmimum normal operating RPM.

Approach: with maximum landing mass following a 6° approach path at a stabilized airspeed corresponding to the best-rate-of-climb speed, again with a rotor-speed stabilized at the maximum normal operating RPM

TEST ENVIRONMENT

Applies to all aircraft

- o no precipitation
- o ambient temperature between 2 °C and 35 °C

- relative humidity between 20% and 95%
- certain combination of the two are to be avoided, where high frequencies are much absorbed
- 30 second average wind speed not to exceed 19 km/h and cross-wind not higher than 9 km/h measured 10 m above ground for (1), (2) and (5), and 1.2 m above ground for (3) and (4)

ADJUSTMENTS TO TEST RESULTS

Note: Differences between test and reference conditions result in differences of the following:

- aeroplane flight path and velocity relative to the measurement point
- amount of sound attenuation in the air
- source noise, i.e. the generating mechanisms of propeller-, rotor- and engine-noise.

Depending on the particular aircraft type, its operation and propulsion system different degrees of adjustments are necessary; within certain test environmental windows, no corrections are necessary.

If the noise evaluation measure is the EPNL, then its computation requires the above listed adjustments; less complex adjustments are required for determining $L_{pA,max}$. This is reflected in the relevant ANNEX 16 Appendix Sections on Data Adjustments.

(1) **Propeller-driven Aeroplanes over 9000 kg**

Corrections are required for

- attenuation of the noise along its path by means of the inverse-square law and atmospheric attenuation
- duration of the noise as affected by distance and speed of the aeroplane relative to the measuring point
- source noise emitted by the engine or the propellers as affected by relevant parameters

(2) **Subsonic Jet Aeroplanes**

Corrections are required for

- attenuation of the noise along its path by means of the inverse-square law and atmospheric attenuation
- duration of the noise as affected by distance and speed of the aeroplane relative to the measuring point
- source noise emitted by the engine or the propellers as affected by relevant parameters

(3) **Propeller-driven Aeroplanes not exceeding 9000 kg** (ACA before 17 Nov. 1988)

Corrections are required for

- engine power,
- helical blade tip Mach number (for a difference of more than 0.003), and
- flight height

(4) **Propeller-driven Aeroplanes not exceeding 9000 kg** (ACA on/after 17 Nov. 1988)

Corrections are required for

- atmospheric attenuation,
- noise path length,
- helical blade tip Mach number, and
- engine power

(5) **Helicopters**

Similar corrections as under (1), (2), and (4) are required for the helicopter; however, the determination of a helicopter's noise sensitivity (dependence of EPNL upon flight speed or Mach-number of the advancing blade) is needed to correct for test/reference-differences in advancing blade tip Mach number and flight speed. The inverse-square-law does not correctly adjust for differences in the flight height on account of the 3 laterally positioned measuring microphones!

TEST RESULT VALIDITY

For all noise certification testing the general requirement has been set to ascertain a large enough test sample (number of valid test flights) to establish statistically a 90% confidence limit not exceeding +/- 1.5 dB (See also Appendix E of this AGARDograph)

APPENDIX D: ATMOSPHERIC ATTENUATION COEFFICIENTS

The following tables concerning the sound attenuation coefficient α in dB/100 m is an excerpt of the more extensive tables as presented e.g. in |1, 3a|

Here tables are reproduced only for relative humidities of 30%, 50%, 70% and 90%. Attenuation coefficients for other relative humidities can be interpolated from the values listed in "neighboring" tables.

Band centre frequency	*Relative humidity = 30%*										
	Temperature, °C										
Hz	−10	−5	0	5	10	15	20	25	30	35	40
50	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
63	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
80	0.1	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
100	0.1	0.1	0.0	0.0	0.0	0.0	0.0	0.0	0.1	0.1	0.1
125	0.1	0.1	0.1	0.1	0.1	0.0	0.1	0.1	0.1	0.1	0.1
160	0.2	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1
200	0.2	0.2	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1
250	0.3	0.2	0.2	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.2
315	0.4	0.3	0.2	0.2	0.2	0.1	0.1	0.1	0.2	0.2	0.2
400	0.6	0.5	0.4	0.3	0.2	0.1	0.2	0.2	0.2	0.2	0.2
500	0.7	0.6	0.5	0.4	0.2	0.2	0.2	0.2	0.3	0.3	0.3
630	0.9	0.9	0.7	0.5	0.3	0.3	0.3	0.3	0.3	0.3	0.4
800	1.1	1.3	1.0	0.8	0.4	0.3	0.3	0.4	0.4	0.4	0.5
1000	1.3	1.6	1.4	1.1	0.6	0.5	0.4	0.5	0.5	0.6	0.6
1250	1.5	2.0	1.9	1.6	0.9	0.7	0.6	0.6	0.6	0.7	0.8
1600	1.7	2.5	2.7	2.2	1.2	0.9	0.8	0.7	0.8	0.9	1.0
2000	1.9	3.0	3.6	3.1	1.8	1.4	1.1	1.0	1.0	1.1	1.3
2500	2.1	3.5	4.4	4.2	2.5	2.0	1.6	1.4	1.3	1.4	1.6
3150	2.3	4.0	5.5	5.9	3.5	2.8	2.2	1.9	1.7	1.8	2.0
4000	2.6	4.5	6.8	7.9	4.9	4.0	3.3	2.6	2.3	2.3	2.5
5000	2.8	4.8	7.4	9.0	6.9	5.8	4.7	3.8	3.3	3.1	3.3
6300	3.2	5.3	8.6	11.1	8.2	6.9	5.7	4.6	3.9	3.6	3.7
8000	3.8	6.1	9.9	13.9	11.3	9.6	8.0	6.6	5.4	4.8	4.7
10000	4.5	7.1	11.4	16.9	15.6	13.6	11.5	9.5	7.9	6.8	6.4
12500	5.5	8.3	13.0	20.0	20.3	19.1	16.6	13.9	11.6	9.7	8.8
					25.3	26.6	23.0	19.6	16.4	13.8	12.1

Band centre frequency	*Relative humidity = 50%*										
	Temperature, °C										
Hz	−10	−5	0	5	10	15	20	25	30	35	40
50	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
63	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
80	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
100	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.1	0.1	0.1
125	0.1	0.0	0.0	0.0	0.0	0.0	0.1	0.1	0.1	0.1	0.1
160	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1
200	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1
250	0.2	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.2
315	0.3	0.2	0.1	0.1	0.1	0.1	0.1	0.1	0.2	0.2	0.2
400	0.4	0.3	0.2	0.2	0.1	0.1	0.2	0.2	0.2	0.2	0.2
500	0.5	0.4	0.3	0.2	0.2	0.2	0.2	0.2	0.3	0.3	0.3
630	0.7	0.6	0.4	0.3	0.2	0.2	0.3	0.3	0.3	0.3	0.4
800	1.0	0.8	0.6	0.5	0.3	0.3	0.3	0.4	0.4	0.4	0.5
1000	1.4	1.1	0.9	0.6	0.4	0.4	0.4	0.5	0.5	0.6	0.6
1250	1.8	1.6	1.2	0.9	0.5	0.5	0.5	0.6	0.6	0.7	0.8
1600	2.3	2.2	1.8	1.3	0.7	0.6	0.7	0.7	0.8	0.9	1.0
2000	2.8	3.1	2.4	1.9	1.0	0.9	0.9	0.9	1.0	1.1	1.3
2500	3.4	4.0	3.4	2.7	1.5	1.2	1.1	1.2	1.3	1.4	1.6
3150	4.0	5.1	4.7	3.8	2.1	1.6	1.5	1.5	1.7	1.8	2.0
4000	4.6	6.4	6.7	5.5	3.0	2.3	2.0	1.9	2.1	2.3	2.5
5000	4.9	7.2	7.9	6.5	4.4	3.4	2.8	2.6	2.7	3.0	3.3
6300	5.4	8.6	10.2	8.9	5.2	4.2	3.4	3.1	3.1	3.4	3.7
8000	6.2	10.2	13.1	12.5	7.3	5.9	4.7	4.1	4.0	4.3	4.7
10000	7.2	11.9	16.4	17.8	10.5	8.6	6.9	5.8	5.4	5.7	6.2
12500	8.4	13.6	20.1	23.4	15.0	12.4	10.2	8.4	7.5	7.4	8.1
					20.6	17.5	14.4	11.9	10.4	9.9	10.5

Band centre frequency	Relative humidity = 70%										
	Temperature, °C										
Hz	−10	−5	0	5	10	15	20	25	30	35	40
50	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
63	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
80	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.1	0.1	0.1
100	0.0	0.0	0.0	0.0	0.0	0.0	0.1	0.1	0.1	0.1	0.1
125	0.0	0.0	0.0	0.0	0.1	0.1	0.1	0.1	0.1	0.1	0.1
160	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1
200	0.1	0.1	0.1	0.1	0.1	0.1	0.2	0.1	0.1	0.1	0.2
250	0.1	0.1	0.1	0.1	0.1	0.1	0.2	0.1	0.2	0.2	0.2
315	0.2	0.1	0.1	0.1	0.1	0.1	0.2	0.2	0.2	0.2	0.2
400	0.3	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.3	0.3	0.3
500	0.4	0.3	0.2	0.2	0.2	0.2	0.3	0.3	0.3	0.4	0.4
630	0.6	0.4	0.3	0.3	0.3	0.3	0.3	0.4	0.4	0.4	0.5
800	0.8	0.6	0.4	0.4	0.4	0.4	0.4	0.5	0.5	0.6	0.6
1000	1.1	0.8	0.6	0.5	0.4	0.5	0.5	0.6	0.7	0.7	0.8
1250	1.5	1.1	0.9	0.7	0.6	0.6	0.7	0.7	0.8	0.9	1.0
1600	2.1	1.7	1.2	0.9	0.8	0.8	0.9	1.0	1.0	1.1	1.3
2000	2.9	2.3	1.8	1.3	1.0	1.0	1.1	1.2	1.3	1.4	1.6
2500	3.7	3.2	2.5	1.9	1.5	1.3	1.4	1.5	1.7	1.8	2.0
3150	4.6	4.4	3.5	2.7	2.1	1.8	1.8	1.9	2.1	2.3	2.5
4000	5.7	6.3	5.1	4.0	3.1	2.5	2.3	2.5	2.7	3.0	3.3
5000	6.3	7.3	6.0	4.7	3.7	3.0	2.7	2.9	3.1	3.4	3.7
6300	7.5	9.3	8.2	6.6	5.2	4.2	3.6	3.6	4.0	4.3	4.7
8000	8.8	11.8	11.6	9.5	7.6	6.1	5.1	4.9	5.2	5.7	6.2
10000	10.2	14.8	16.4	13.7	11.1	9.0	7.4	6.8	6.8	7.4	8.1
12500	11.6	18.0	21.4	18.8	15.7	12.8	10.5	9.2	9.0	9.6	10.5

Band centre frequency	Relative humidity = 90%										
	Temperature, °C										
Hz	−10	−5	0	5	10	15	20	25	30	35	40
50	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
63	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
80	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.1	0.1	0.1
100	0.0	0.0	0.0	0.0	0.0	0.0	0.1	0.1	0.1	0.1	0.1
125	0.0	0.0	0.0	0.0	0.1	0.1	0.1	0.1	0.1	0.1	0.1
160	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1
200	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.2
250	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.2	0.2	0.2
315	0.1	0.1	0.1	0.1	0.1	0.1	0.2	0.2	0.2	0.2	0.2
400	0.2	0.2	0.1	0.2	0.2	0.2	0.2	0.2	0.3	0.3	0.3
500	0.3	0.2	0.2	0.2	0.2	0.2	0.3	0.3	0.3	0.3	0.4
630	0.4	0.3	0.2	0.2	0.3	0.3	0.3	0.4	0.4	0.4	0.5
800	0.6	0.4	0.3	0.3	0.3	0.4	0.4	0.5	0.5	0.6	0.6
1000	0.9	0.6	0.5	0.4	0.4	0.5	0.5	0.6	0.6	0.7	0.8
1250	1.2	0.9	0.6	0.5	0.6	0.6	0.7	0.7	0.8	0.9	1.0
1600	1.7	1.3	0.9	0.7	0.7	0.8	0.9	0.9	1.0	1.1	1.3
2000	2.4	1.8	1.3	1.0	0.9	1.0	1.1	1.2	1.3	1.4	1.6
2500	3.3	2.6	1.9	1.4	1.2	1.3	1.4	1.5	1.7	1.8	2.0
3150	4.6	3.6	2.8	2.1	1.7	1.6	1.8	1.9	2.1	2.3	2.5
4000	6.0	5.1	4.0	3.0	2.4	2.2	2.3	2.5	2.7	3.0	3.3
5000	6.7	6.0	4.8	3.7	2.9	2.6	2.6	2.8	3.1	3.4	3.7
6300	8.3	8.3	6.7	5.2	4.0	3.4	3.3	3.6	4.0	4.3	4.7
8000	10.4	11.7	9.5	7.6	6.0	4.9	4.5	4.8	5.2	5.7	6.2
10000	12.6	15.4	13.5	11.0	8.8	7.1	6.3	6.3	6.8	7.4	8.1
12500	14.8	19.4	18.6	15.4	12.4	10.1	8.7	8.3	8.9	9.6	10.5

APPENDIX E: ESTABLISHMENT OF THE VALIDITY OF TEST RESULTS

Evaluation of noise certification data from flyovers of subsonic jet-aeroplanes, heavy propeller-driven aeroplanes and helicopters involves the averaging of the (final, and corrected) EPN-levels as obtained during repeated test-flights. A minimum of six valid test-flights is specified. Further, the sample-size (of the acoustic data) must be large enough to establish a confidence-limit not to exceed +/-1.5 EPNdB at a 90% confidence level.

Assume, the following EPNL-values for N = 6 flights had been determined for a particular flight procedure, e.g. take-off test flight

Test flight number (i=)	1	2	3	4	5	6
EPNL (dB)	83	81	83	85	83	85

These values could be classified and plotted in terms of a statistical point-diagram (Fig. E-1)

The values yield the following arithmetic mean $\overline{EPNL} = \bar{x}$, and standard deviation, s_x, resp. with N = 6:

(E1) $$\overline{EPNL} = \bar{x} = \frac{\sum_{i=1}^{N} EPNL_i}{N} = 83.3 \text{ dB}$$

(E2) $$s_x = \left[\frac{\sum_{i=1}^{N} \left(EPNL_i - \overline{EPNL}\right)^2}{N-1} \right]^{1/2} = 1.5 \text{ dB} \quad .$$

Although there are really only very few data points, we assume for the present that they formed a sample drawn from a Gaussian population, whose normal distribution however was based on an "infinite" number of items (infinite sample size). The calculated mean $\bar{x}$ and the standard deviation s then must be considered to represent the 'best estimate' of the true mean μ, and of the true standard deviation σ of an infinite sample.

Now for a required confidence level of, say, 90% or 95% (corresponding to an error probability α of 0.10 or 0.05, respectively) one may establish a confidence interval (or its limits) in which (or within which) μ must be assumed with the selected probability. For an infinite sample (N = ∞) the confidence limits would, respectively, be $u_{\infty;0.10} = +/-1.645\sigma$, and $u_{\infty;0.05} = +/-1.960\sigma$.

Since only s_x as an estimate of σ , rather then σ itself, is known, one must account for the fact that the sample sizes are neither infinite, nor even very large, but - on the contrary - very small. This now is taken into account with Gosset's so-called 'Student-distribution' or t-distribution |63|

The distribution of t depends on the sample size N, or more exactly on the 'degrees of freedom' f = N - 1; it assumes a bell-shape distribution, just as the Gaussian distribution does, but is broader depending on the degrees of freedom. For N = 2 it is broadest (with one degree of freedom only); with increasing sample size the t-distribution more and more approaches the normal distribution, eventually coinciding when the sample size becomes infinite (N = ∞).

We are now able to calculate the confidence limits for a small sample

(E3) $$u_{N-1;} = +/- \frac{s_x \cdot t_{N-1;}}{\sqrt{N}} \quad ;$$

or the confidence interval

(E4) $\bar{x} - u_{N-1;\alpha} < \mu < \bar{x} + u_{N-1;\alpha}$

which describe the uncertainty of our estimator $\bar{x}$ due to random sampling of only very few items of a basic population with respect to a 'true' μ, which is only a 'true' one for this specific test!

The values of t are tabulated for various error-probabilities and degrees of freedom in Table E-1.

For samples of N = 6 items (i.e. f = N - 1 = 5) and an error probability of 0.10 one reads $t_{5;0.10} = 2.015$ for a two-sided limitation. To determine the lower and upper limits ('left' or 'right') for the calculated mean of our example, one obtains for the confidence limit:

(E5) $$u_{0.1} = \frac{s_x \cdot t_{5;0.1}}{\sqrt{N}} = 1.24 \text{ dB}$$

This value of 1.24 dB for a 90% confidence level is well within the (ICAO/ANNEX 16) allowance of +/-1.5 dB. The corresponding confidence-interval would be 82.1 μ 84.5

Conversely, since a +/-1.5 dB excess is permitted, the allowable maximum standard deviation for 6 samples would be

(E6) $$s_{x\,max} = \frac{1.5 \sqrt{N}}{t_{5;0.1}} = 1.82 \text{ dB.}$$

The maximum permissible standard deviation as function of sample size (i.e. the number of flyovers) for a confidence limit not exceeding +/-1.5 dB at 90% confidence level is shown in Fig. E-2.

Obviously, if the error-probability is to be reduced (i.e. the confidence level to be increased) then the limits of the confidence-interval themselves move apart, as a consequence of a growth of $(s_x \cdot t_{N-1;\alpha})/\sqrt{N}$ and vice versa.

Thus, if a higher confidence level of, say, 95% was required (corresponding to a 5% error probability) then the limitc would mcve further apart, i.e.

(E7) $$83.3 - 2.57 \frac{s_x}{\sqrt{N}} < \mu < 83.3 + 2.57 \frac{s_x}{\sqrt{N}}$$

or $$81.8 < \mu < 84.9.$$

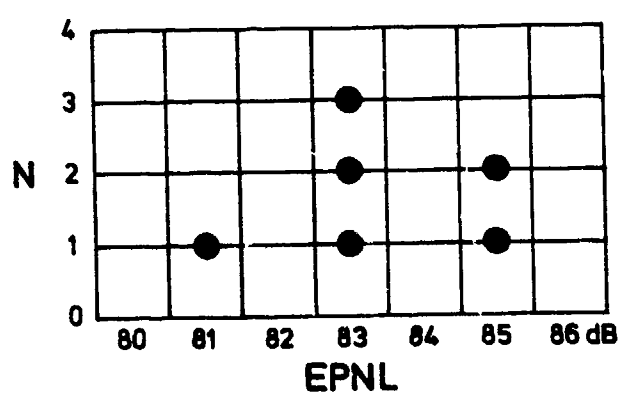


Fig. E-1 Example of a statistical frequency distribution of EPNL values in 1 dB classes

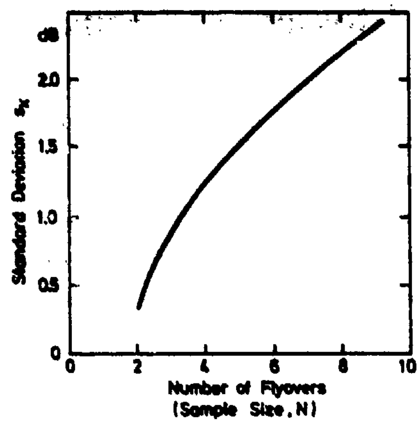
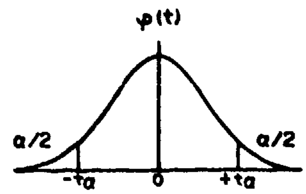


Fig. E-2 Maximum permissible standard deviation $s_{\bar{x}}$ as function of the number of flyovers ("sample size") for a 90% confidence limit not exceeding +/- 1.5 dB

TABLE E-1 t-distribution for various error probabilities α and degrees of freedom (from Ref. 64)

n	α = 0.20	α = 0.10	α = 0.05	α = 0.02	α = 0.01	n
1	3.078	6.314	12.706	31.821	63.657	1
2	1.886	2.920	4.303	6.965	9.925	2
3	1.638	2.353	3.182	4.541	5.841	3
4	1.533	2.132	2.776	3.747	4.604	4
5	1.476	2.015	2.571	3.365	4.032	5
6	1.440	1.943	2.447	3.143	3.707	6
7	1.415	1.895	2.365	2.998	3.499	7
8	1.397	1.860	2.306	2.897	3.355	8
9	1.383	1.833	2.262	2.821	3.250	9
10	1.372	1.812	2.228	2.764	3.169	10
11	1.363	1.796	2.201	2.718	3.106	11
12	1.356	1.782	2.179	2.681	3.055	12
13	1.350	1.771	2.160	2.650	3.012	13
14	1.345	1.761	2.145	2.625	2.977	14
15	1.341	1.753	2.131	2.603	2.947	15
16	1.337	1.746	2.120	2.584	2.921	16
17	1.333	1.740	2.110	2.567	2.898	17
18	1.330	1.734	2.101	2.552	2.878	18
19	1.328	1.729	2.093	2.540	2.861	19
20	1.325	1.725	2.086	2.528	2.845	20
21	1.323	1.721	2.080	2.518	2.831	21
22	1.321	1.717	2.074	2.508	2.819	22
23	1.319	1.714	2.069	2.500	2.807	23
24	1.318	1.711	2.064	2.492	2.797	24
25	1.316	1.708	2.060	2.485	2.787	25
26	1.315	1.706	2.056	2.479	2.779	26
27	1.314	1.703	2.052	2.473	2.771	27
28	1.313	1.701	2.048	2.467	2.763	28
29	1.311	1.699	2.045	2.462	2.756	29
30	1.310	1.697	2.042	2.457	2.750	30
40	1.303	1.684	2.021	2.423	2.704	40
60	1.296	1.671	2.000	2.390	2.660	60
80	1.292	1.664	1.990	2.374	2.639	80
120	1.289	1.658	1.980	2.358	2.617	120
∞	1.282	1.645	1.960	2.326	2.576	∞



Glossary of Terms

Acoustics Science of all aspects relating to sound

Airframe Noise Noise generated by an aircraft in flyover in the absence of engine noise by aerodynamic interaction of flow and structural components

Ambient noise (see "Background Noise")

Audio frequency range Range of audible sound (approximately from 16 Hz to 16.000 Hz)

Background noise Noise from sources unrelated to a particular sound that is the object of interest

Band pressure level Sound pressure level of the sound energy within a specified frequency band (such as 1/3-octave band or 1/1-octave band)

Confidence limits Upper and lower values of the range over which a per-cent probability applies

Continuous spectrum Spectrum of a wave, whose components are continuously distributed over the frequency range

Crest factor Ratio of the peak value to the rms value of an oscillating quantity

Decibel Ten times the common logarithm of the ratio of two like quantities proportional to power or energy or twenty times for amplitude or pressure

Derived Version A 'Derived Version' of an aircraft (in ICAO's definition) is similar to the prototype (from the point of airworthiness) but incorporates changes in type design which may affect its noise characteristics

Diffraction Directional change of propagation of sound energy near a boundary discontinuity such as the "edge" of an aerodynamic shear layer

Diffuse sound field Sound field where the sound pressure level is essentially the same everywhere

Direct sound field Regime where sound arrives directly from a source without any prior reflection

Directional microphone A microphone whose response depends on the direction of sound incidence

Directivity factor (for an acoustic source) Ratio of sound intensity at a remote point on a reference axis, to the average for all directions in space of the intensity of the sound at the same distance from the effective centre of the source

Directivity factor (for a microphone) Square of the ratio of the free-field sensitivity in a reference direction to the random incidence sensitivity

Dissipation Conversion of sound energy into heat

Doppler effect Change in the observed frequency caused by the time rate of change in the length of the path between the source and the observer

Effective sound pressure The root-mean-square (rms) sound pressure

Emission of Sound The radiation of sound away from the source

Excess attenuation Attenuation of the sound propagated which is not accounted for by spherical spreading losses (e.g. atmospheric absorption or over ground absorption)

Far field Part of the field of a source radiating sound in **free-field** conditions, where sound-pressure and particle velocity are in-phase

Free-field Soundfield in an acoustically essentially unobstructed environment

Harmonic Sinusoidal quantity of frequency that is an integral multiple of the fundamental frequency of a periodic quantity to which it is related

Immission of Sound The impingement of sound at the recipient (observer, ground, microphone, etc)

Level Logarithm of the ratio of a quantity to a reference quantity of the same kind

Near field Part of the field of a source radiating sound in **free-field** conditions, where the sound pressure and particle velocity are not in phase.

Noise Sound that is undesired by or obtrusive to the recipient

Octave Frequency interval of 2:1

Omnidirectional microphone Microphone with response independent of the sound incidence direction

Peak sound pressure The maximum absolute value of the instantaneous sound pressure for a specified time interval

Peak to peak amplitude The algebraic difference between the extremes of an oscillating quantity

Pink noise Noise which has a continuous frequency spectrum and a constant power within a bandwidth proportional to the center frequency of the band

Plane wave A wave in which the wavefronts are parallel planes normal to the direction of propagation

Point source A source that radiates sound as if it were radiated from a single point

Power spectrum The spectrum of the sound as expressed in terms of the spectral density

Pure tone Sound wave whose instantaneous sound pressure is a simple sinusoidal function of time

Random noise Noise whose amplitudes are stochastically distributed over the frequency range

Reflection Directional change within the first medium when a wave front impinges on a boundary between two media

Refraction Process by which the direction of sound propagation is changed because of spatial variation of the wave velocity in the medium

Replication Refers to a way in statistical data evaluation to estimate the experimental error while at the same time providing for its diminuition

Repeatability Refers to tests performed at short intervals in one laboratory by one operator with the same equipment (with no change in environmental parameters such as temperature, humidity, wind etc.)

Reproducibilty Refers to tests performed in different laboratories with different operators and different equipment

Reverberant field Sound field resulting from the superposition of many sound waves due to repeated reflections at the boundaries

Root mean square (RMS) value The square root of the mean value of the squares of the instantaneous values of the quantity; in the case of a periodic variation the mean is taken over one period

Scattering Irregular and diffuse reflection, refraction, or diffraction of sound in many directions

Signal-to-noise level The (desired) signal level minus the (undesired) noise level

Sound absorption Process of dissipating sound energy

Sound absorption coefficient Fraction of the incident sound power which is absorbed by the medium

Sound Exposure Level (SEL) The constant level which - if maintained for a period of 1 second - would have the same acoustic energy as the transient measured one-time noise event

Sound intensity Average rate of energy flow in a specified direction divided by the area through which it flows

Sound power Rate at which acoustic energy is radiated from a source

Sound power level Ten times the common logarithm of the ratio of the sound power to the reference sound power (1pW)

Sound pressure Fluctuating pressure superimposed on the static pressure by the presence of sound

Sound pressure level Ten times the common logarithm of the ratio of the square of the sound pressure to the square of the standard reference pressure of 20 μPa

Sound pressure spectrum The spectrum of a sound expressed in terms of the root-mean square pressure per unit bandwidth

Spherical wave A wave where the wavefronts are concentric spheres

Transducer A device to convert acoustical energy into electrical energy

Wave front Continuous surface whereupon the phase is the same at any given instant

Waveform The shape of the graph representing the successive values of a varying quantity such as sound pressure

Wavelength Distance between two successive points on the wave which are separated by one period

Weighting A prescribed frequency response provided in a sound level meter

White noise Noise of a statistically random nature having equal energy per unit frequency bandwidth over a specified frequency band

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Annex 1

AGARD Flight Test Instrumentation and Flight Test Techniques Series

1. Volumes in the AGARD Flight Test Instrumentation Series, AGARDograph 160

Volume Number	*Title*	*Publication Date*
1.	Basic Principles of Flight Test Instrumentation Engineering by A.Pool and D.Bosman (under revision)	1974
2.	In-Flight Temperature Measurements by F.Trenkle and M.Reinhardt	1973
3.	The Measurement of Fuel Flow by J.T.France	1972
4.	The Measurement of Engine Rotation Speed by M.Vedrunes	1973
5.	Magnetic Recording of Flight Test Data by G.E.Bennett	1974
6.	Open and Closed Loop Accelerometers by I.Mclaren	1974
7.	Strain Gauge Measurements on Aircraft by E.Kottkamp, H.Wilhelm and D.Kohl	1976
8.	Linear and Angular Position Measurement of Aircraft Components by J.C. van der Linden and H.A.Mensink	1977
9.	Aeroelastic Flight Test Techniques and Instrumentation by J.W.G. van Nunen and G.Piazzoli	1979
10.	Helicopter Flight Test Instrumentation by K.R.Ferrell	1980
11.	Pressure and Flow Measurement by W.Wuest	1980
12.	Aircraft Flight Test Data Processing — A Review of the State of the Art by L.J.Smith and N.O.Matthews	1980
13.	Practical Aspects of Instrumentation System Installation by R.W.Borek	1981
14.	The Analysis of Random Data by D.A.Williams	1981
15.	Gyroscopic Instruments and their Application to Flight Testing by B.Stieler and H.Winter	1982
16.	Trajectory Measurements for Take-off and Landing Test and Other Short-Range Applications by P. de Benque d'Agut, H.Riebeek and A.Pool	1985
17.	Analogue Signal Conditioning for Flight Test Instrumentation by D.W.Veatch and R.K.Bogue	1986
18.	Microprocessor Applications in Airborne Flight Test Instrumentation by M.J.Prickett	1987
19.	Digital Signal Conditioning for Flight Test by G.A.Bever	1991

2. Volumes in the AGARD Flight Test Techniques Series

Number	*Title*	*Publication Date*
AG237	Guide to In-Flight Thrust Measurement of Turbojets and Fan Engines by the MIDAP Study Group (UK)	1979

The remaining volumes are published as a sequence of Volume Numbers of AGARDograph 300.

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1.	Calibration of Air-Data Systems and Flow Direction Sensors by J.A.Lawford and K.R.Nippress	1983
2.	Identification of Dynamic Systems by R.E.Maine and K.W.Iliff	1985
3.	Identification of Dynamic Systems — Applications to Aircraft Part 1: The Output Error Approach by R.E.Maine and K.W.Iliff	1986
4.	Determination of Antenna Patterns and Radar Reflection Characteristics of Aircraft by H.Bothe and D.McDonald	1986
5.	Store Separation Flight Testing by R.J.Arnold and C.S.Epstein	1986
6.	Developmental Airdrop Testing Techniques and Devices by H.J.Hunter	1987
7.	Air-to-Air Radar Flight Testing by R.E.Scott	1988
8.	Flight Testing under Extreme Environmental Conditions by C.L.Henrickson	1988
9.	Aircraft Exterior Noise Measurement and Analysis Techniques by H.Heller	1991

At the time of publication of the present volume the following volumes were in preparation:

Identification of Dynamic Systems. Applications to Aircraft.
Part 2: Nonlinear Model Analysis and Manoeuvre Design
by J.A.Mulder and J.H.Breeman

Flight Testing of Terrain Following Systems
by C.Dallimore and M.K.Foster

Store Ballistic Analysis and Testing
by R.Arnold and H.Reda

Reliability and Maintainability
by J.Howell

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by J.D.L.Gregory

Flight Testing of Air-to-Air Refuelling of Fixed Wing Aircraft
by J.Bradley and K.Em

Introduction to Flight Test Engineering
Edited by F.Stoliker and H.Torode

Operational Flight Testing
by M.Williams et al.

Space System Testing
by A.Wisdom

Annex 2

Available Flight Test Handbooks

This annex is presented to make readers aware of handbooks that are available on a variety of flight test subjects not necessarily related to the contents of this volume. It is not necessarily a full listing of such documents.

Requests for A & AEE documents should be addressed to the Defence Research Information Centre, Glasgow (see back cover). Requests for US documents should be addressed to the Defence Technical Information Center, Cameron Station, Alexandria, VA 22314 (or in one case, the Library of Congress).

Number	*Author*	*Title*	*Date*
AFFTC-TIH-88-004	Hendrickson, C.L.	Flight Testing Under Extreme Climatic Conditions	1988
AFFTC-TIM-75-11	Pihlgren, W.D.	Aircraft Vertical Center of Gravity Determination Using the Ground Inclination Method	1975
AFFTC-TIH-84-1	Lush, K.J.	Electrical Subsystems Flight Test Handbook	1984
AFFTC-TIH-83-2	Lush, K.L.	Hydraulic Subsystems Flight Test Handbook	1983
AFFTC-TIH-82-2	Lush, K.L.	Environmental Control Subsystems Flight Test Handbook	1982
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—	—	Pilot's Handbook for Critical and Exploratory Flight Testing. (Sponsored by AIAA & SETP — Library of Congress Card No.76-189165)	1972
—	—	A & AEE Performance Division Handbook of Test Methods for assessing the flying Qualities and Performance of Military Aircraft. Vol.1 Airplanes (A/L 9 1989)	
A & AEE Note 2111	Appleford, J.K.	Performance Division: Clearance Philosophies for Fixed Wing Aircraft	1978
A & AEE Note 2113 (Issue 2)	Norris, E.J.	Test Methods and Flight Safety Procedures for Aircraft Trials Which May Lead to Departures from Controlled Flight	1980
A & AEE ARM 1014/03	—	A & AEE Armament Division Handbook of Test Methods	

175

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14. Abstract

This volume

This volume in the AGARD Flight Test Techniques Series describes testing and analysis techniques to measure aircraft noise primarily for purposes of noise certification as specified by the International Civil Aviation Organization, ICAO. The relevant aircraft noise certification 'Standards' and 'Recommended Practices' are presented in detail for subsonic jet aeroplanes, for heavy and light propeller-driven aeroplanes and for helicopters. The practical execution of conducting noise certification tests is treated in depth. The characteristics and requirements of the acoustic and non-acoustic instrumentation for data acquisition and data processing are discussed, as are the procedures to determine the special noise measures 'Effective Perceived Noise Level' (EPNL) and 'Maximum Overall A-weighted Noise Level' ($L_{pA,max}$) that are required for the noise certification of different types of aircraft.

The AGARDograph also contains an extensive -- although selective -- discussion of test and analysis techniques for more detailed aircraft noise studies by means of either flight experiments or full-scale and model-scale wind tunnel experiments. Appendices provide supplementary information.

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

AGARDograph No.300 Volume 9
Advisory Group for Aerospace Research and Development, NATO
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The AGARDograph also contains an extensive — although selective — discussion of test and analysis techniques for more detailed aircraft noise studies by means of either flight-experiments or full-scale and model-scale wind tunnel experiments. Appendices provide supplementary information.

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