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7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES):
QUANTITATIVE MORPHOLOGY CONSULTING
P.O. BOX 6273
SAN DIEGO, CA 92166

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OFFICE OF NAVAL RESEARCH
800 N. QUINCY ST
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14. ABSTRACT

Dolphin click generators were studied via anatomy, tissue properties, physiology, and acoustic analyses. Our objective was to design, produce, and test computational models and physical devices that mimic dolphin sonar signal generation. Our multi-mass computational model of dolphin click production was based the Steinecke-Herzel model of the human larynx. We developed and implemented an acoustic model that translates the motions from our multi-mass model into acoustic signals. We also mastered CNC controlled milling machine and lathe operations to produce physical prototypes of biomimetic sound sources, complete with dolphin-like phonic lips and a pneumatic driver.

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FINAL REPORT

GRANT #: N00014-01-1-0683
PRINCIPAL INVESTIGATOR: Dr. Ted W. Cranford
INSTITUTION: Quantitative Morphology Consulting
GRANT TITLE: Biomimetic Dolphin Sonar Source
AWARD PERIOD: 15 April 2001 - 30 September 2003

OBJECTIVE: To design, produce, and test computational models and physical devices that mimic dolphin sonar signal (click) generation.

APPROACH: This effort is built upon a foundation of anatomic and physiologic data. Using these data, we implemented computational models of the tissue motions responsible for click production. The models are based upon extensively tested models of human sound production (Flanagan, et al. 1975; Steinecke and Herzel, 1995). We considered the acoustic waveform resulting from the dipole motion of the masses, the pressure relationships and Bernoulli forces, and the tissue properties. We also calculated the potential effect of depth on the work needed for click production to occur. Our approach involved mathematical modeling and prototype engineering efforts.

ACCOMPLISHMENTS: We constructed and tested two simple mathematical models, one that includes mechanical components and accounts for their relative motions or displacements. The second model predicts the acoustic dipole field generated from those displacements. The parameters of the dolphin's sound generation apparatus were encoded in the model and subsequently evaluated. The parameters of the computational model were varied systematically and the results reevaluated to determine the most promising direction for development of physical models. Several simple prototypes have been constructed based upon the best computational modeling results and what we know about dolphin physiology.

Our mathematical model of source motion approximates the kinematics of the dolphin's sonar signal generator by simulating the flow of pressurize air, the motion of multiple masses, and the action of various springs and dashpots. Evolutionary computation techniques were applied to this model to explore the parameter space and incorporated physical constraints on the system. This had the effect of reducing the apparent parameter space. A set of parameters was identified based upon initial input values from dolphin anatomy and physiology.

The result of running the source motion was a set of motion data for four masses. An acoustic model based on dipole radiation was developed to use these multi-mass motions as input and predict the amplitude at a given point in the sound field as output.

The pneumatic hypothesis of click sound production (Cranford, 2000) predicts tissue motion and velocities consistent with the initial kinematics analysis. This analysis showed us that the values for range of motion, final velocity, and resulting amplitude of clicks are reasonable for the biological tissues involved. It also signifies that our hypothesis of sound production is in agreement with an independent analysis of the underlying physics.

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We evaluated cavitation as an alternative mechanism of click sound production. Working from a relationship between a particular pressure in water and conditions necessary for cavitation, we predicted source levels if cavitation were the mechanism of click production. We also showed that *cavitation is **not** supported* when click source levels and the measured directivity index for bottlenose dolphins are considered.

The computational modeling efforts produced the significant finding that the rapid acceleration during collision gives rise to the acoustic phenomena we associate with dolphin clicks: short duration, wide bandwidth, and high amplitude. The computational model can produce both clicks and whistles, just as we have observed in dolphins. By changing two of the parameters of the system (higher source pneumatic pressure and stiffer "springs" associated with the masses), whistles were produced instead of clicks. The model essentially describes a linear system whose dynamics are driven by two nonlinear processes. One of these processes is the Bernoulli flow of gas between tissues. The other is the collision between tissues.

A series of pneumatically-driven prototype sound sources were produced. Computer-numeric controlled desktop machine tools were used to produce parts and molds. These physical models iteratively incorporated features from the dolphin biosonar system. The most significant finding is that building an air space behind the vibratory element is key to producing dolphin-like sound generation function.

The series of physical prototypes led to further insights into the probable function of the anatomy of the dolphin. The prototypes were machined such that the opposing sets of lips could be made in a single casting. These were progressively made with more correspondence to the complexity indicated by the dolphin anatomy.

CONCLUSIONS: These biomimetic sound sources could probably be fully developed and scaled up for long range applications based upon similarities in the sperm whale sound generation system.

SIGNIFICANCE: Bottlenose dolphins produce biosonar signals that have several properties desirable for use in man-made sonar applications. Biomimetic sonar sources could be pneumatically powered and designed into a small, low drag (hydrodynamic) package that delivers significant power efficiently across a broad bandwidth.

PATENT INFORMATION: The prototype physical models are not fully developed and are currently not ready to be deployed in operational systems. No patents have been applied for any devices.

AWARD INFORMATION:

- **Invited Plenary** (2001) for the Symposium on Bio-sonar and Bioacoustics. (Loughborough, U.K.).
- **Fairfield Award for Innovative Marine Mammal Research**, (Elsberry et al. 2001). The 14th Biennial Conference on the Biology of Marine Mammals (Vancouver, British Columbia).
- **Invited Plenary** (2003) for the 17th European Cetacean Society Meeting, (Las Palmas de Gran Canaria, Spain).

- **Best Student Poster Award,** (McKenna et al. 2003). The 15th Biennial Conference on the Biology of Marine Mammals (Greensboro, North Carolina).

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2. Goodson, D. A., Flint, J. A. and Cranford, T. W. (2003). The Harbor Porpoise (*Phocoena phocoena*) - Modeling the sonar transmission mechanism. In *Echolocation in Bats and Dolphins* (eds. J. A. Thomas, C. F. Moss and M. Vater). Pp. 64-71, Chicago: University of Chicago Press.

3. Cranford, T.W., (2000) In Search of Impulse Sound Sources in Odontocetes. *In* Hearing by Whales and Dolphins (Springer Handbook of Auditory Research series), W.W.L. Au, A.N. Popper and R.R. Fay, Eds. Springer-Verlag, New York, pp. 109-156.

4. Cranford, T. W., W. R. Elsberry, W.G. Van Bonn, J.A. Carr, D.J. Blackwood, D.A. Carder, T. Kamolnick, M. Todd, S.H. Ridgway. (In Review). "Interrelationships between intranarial pressure and biosonar clicks in the bottlenose dolphin (*Tursiops truncatus*)." J. Acoust. Soc. Am.

5. Elsberry, W. R., T. W. Cranford, W.G. Van Bonn, J.A. Carr, D.J. Blackwood, D.A. Carder, T. Kamolnick, M. Todd, S.H. Ridgway. (In Review). "Bioenergetics of individual pressurization events in the bottlenose dolphin (*Tursiops truncatus*)." J. Acoust. Soc. Am.

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7. Soldevilla, M., M. McKenna, S. Wiggins, R. Shadwick, T. Cranford, and J. Hildebrand. (In Review) "Interaction of Sound with Beaked Whale Tissues: Physical Properties from *Ziphius cavirostris*." Journal of Experimental Biology.

8. Cranford, T.W., and C.R. Schilt, (In revision) Sounds produced by a captive pygmy sperm whale (*Kogia breviceps*). J. Acoust. Soc. Am.

Abstracts:

9. Cranford, T.W., W.R. Elsberry, W.G. Van Bonn, J.A. Carr, D.J. Blackwood, D.A. Carder, T. Kamolnick, M. Todd, S.H. Ridgway (2001). Anatomy and Physiology of Bilateral Sonar Signal Generation in the Bottlenose Dolphin. The 14th Biennial Conference on the Biology of Marine Mammals, (Vancouver, British Columbia, Canada)

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11. Cranford, T.W., W.R. Elsberry, W.G. Van Bonn, J.A. Carr, D.J. Blackwood, D.A. Carder, T. Kamolnick, M. Todd, S.H. Ridgway (2001). Dolphin Biosonar Sound Sources: Volume, Pressure, and Process. Invited for the Symposium on Bio-sonar and Bioacoustics. (Loughborough, U.K.).

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14. Cranford, T.W., M. Hock, M. McKenna, S. Wiggins, R. Shadwick, A. Sauter, G. Armsworthy, P. Krysl, J. Hildebrand (2003). Building An Acoustic Model Of A Cuvier's Beaked Whale (*Ziphius cavirostris*). Invited Plenary for Proceedings of the 17th European Cetacean Society, (Las Palmas de Gran Canaria, Spain).

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19. McKenna, M.F., M. Soldvilla, A. Berta, and T.W. Cranford, (2003). Comparative Morphology of the Odontocete Melon: A foundation for functional and evolutionary interpretations. The 15th Biennial Conference on the Biology of Marine Mammals (Greensboro, North Carolina).

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