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Mid-Frequency Sonar Interactions with Beaked Whales

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LONG-TERM GOALS

The top-level goal of this project was to build an interactive online modeling and visualization system, called the Virtual Beaked Whale, to enable users to predict mid-frequency sonar-induced acoustic fields inside beaked whales and other marine mammals. Another high-level goal was to acquire new high-resolution morphometric and physical-property data on beaked whales for use in the model. It was hoped that the availability of such a system together with high-quality data would give researchers insight into the nature of sonar interactions with beaked whales, ultimately to introduce objectivity into a public discussion that has been hampered by lack of a scientific approach. It was hoped further that the tool would prove useful in evaluating alternate sonar transmit signals that retain the required information content but with substantially reduced physical effects in beaked whales.

OBJECTIVES

To achieve the long-term goals, a number of scientific and technological objectives were identified. These included the following: extending existing finite-element-method (FEM) code to describe acoustic interactions with structures, and applying this to a virtual beaked whale and mid-sonar frequencies in the range 1–10 kHz; collecting high-resolution morphometric data through computerized tomography (CT) scans on marine mammal specimens, and constructing finite-element models of the anatomy; assigning physical properties of tissues; benchmarking the finite-element code; and incorporating the extended finite-element code and morphometric and physical-property data in an online modeling and visualization system called the Virtual Beaked Whale.

APPROACH

The approach followed an integrated set of six tasks, which are briefly described.

Task 1. Development of a finite-element method to model acoustic interactions: This task was considered as a structural-acoustic problem, in which most tissue groups and surrounding water behave as acoustic fluids and, bony tissues behave as elastic solids. A beaked whale or other marine mammal was to be modeled as a structure represented by its morphometry (Task 2), in which each anatomical part is assigned its own set of physical properties (Task 3).

Task 2. Morphometry and meshing the three-dimensional anatomy: The principal source of morphometric data were CT scans performed at the Woods Hole Oceanographic Institution (WHOI) Computerized Scanning and Imaging (CSI) Facility. Image data on marine mammal specimens were expressed in Digital Imaging and Communications in Medicine (DICOM) format. Amira (Visage Imaging, Inc., San Diego, CA) visualization software was used for segmentation and surface reconstruction. The automatic mesh generation employed tetrahedral elements.

Task 3. Physical properties of tissues: The best available data were to be used to represent the acoustically important properties of mass density, elastic constants, and absorption coefficients for each identified internal organ or other body part.

Task 4. Measuring interactions of acoustic fields with cetacean specimens: In order to test the FEM code (Task 1), measurements were performed of the internal pressure field in selected tissues in an instrumented common dolphin cadaver, also referred to in this report as a specimen. The specimen was prepared by surgically implanting acoustic sensors in the form of tourmaline pressure gauges; CT-scanned to determine sensor location and morphometry; then acoustically measured at the Naval Surface Warfare Center (NSWC) Carderock Division. A necropsy was performed within hours of the experiment.

Task 5. Testing the FEM model: Rigorous testing was to be performed by comparison with analytic solutions for immersed simple objects. These solutions were developed and numerically realized for acoustically absorptive fluid spheres and solid elastic spheres in a lossy immersion fluid. Numerical solutions for more complicated objects were also identified.

Task 6. Virtual Beaked Whale: This interactive online modeling and visualization system was to be the principal deliverable of the project. It was to incorporate a database with sets of whole-body morphometric data (Task 2) from beaked whales and other species, as well as the respective physical

properties of tissues (Task 3). It would also allow users to enter other morphometric and physical-property data directly. The user would be able to specify an essentially arbitrary mid-frequency sonar signal. The output would consist of computed solutions for the internal pressure and displacement fields (Task 1) at user-specified locations.

WORK COMPLETED

Task 1. Development of a finite-element method to model acoustic interactions

Completed in earlier years.

Task 2. Morphometry and meshing the three-dimensional anatomy

2011: The synthesis process was completed and publication was initiated on the CSI website [http://csi.whoi.edu/].

Task 3. Physical properties of tissues

2011: An attempt was made to survey the literature on acoustically significant properties of cetacean tissues. These properties are allowed to subsume the conventional physical properties of mass density, sound speed, compressibility, and their pressure and temperature dependences; anatomical properties, including morphology and topology; and biochemistry, including molecular composition. The source literature is diverse, reflecting the many interesting aspects of cetacean tissue properties. These span such issues as buoyancy with respect to temperature and pressure, recognizing that lipids undergo a phase change within the ordinary diving range of sperm whales and other odontocetes; role of blubber; audiology; and sound generation, including echolocation. The importance of lipid composition with tissue location is appreciated apropos of sound propagation (Koopman et al. 2003, 2006; Duggan et al. 2009). Duggan et al. (2009) noted the relationship of carbon chain length to sound speed, which is inverse (Gouw and Vlugter 1967, Hustad et al. 1971).

It is observed from the table that the measurements and reported data are quite limited. Notable exceptions are works dating from Soldevilla et al. (2005), which attempt to represent the physical properties of cetacean tissues in a comprehensive manner that would be self-sufficient for modeling purposes. In Soldevilla et al. (2005) and some other studies, the mass density of tissues was assumed to be accessible through the X-ray absorption measurements that are fundamental to computed tomography (CT), and conversion from Hounsfield units to units of mass density were effected through calibrations that can be traced to measurements on phantom targets of known mass density. The represented acoustic properties also included absorption.

Determination of the physical properties of cetacean tissues represents an outstanding problem that has attracted attention and funding. Thus far, tools or methods to accomplish such measurements *in vivo* are wanting. Inference of tissue properties by a combined program of measurement of sonar-induced fields inside instrumented specimens and modeling may be the most effective approach. Certainly the issue of data quality is important when justifying conclusions being drawn from modeling studies about the physical effects of sonar.

Task 4. Measuring interactions of acoustic fields with cetacean specimens

2011: Analysis of the experiment was completed, and a manuscript was prepared and submitted for publication (Foote et al., submitted).

The tourmaline sensors first used in sub-shock measurements in 2008, and reported above, were documented in preliminary form (Morales et al. 2011).

Task 5. Testing the FEM model
Completed in earlier years.

Task 6. Virtual Beaked Whale
Completed in earlier years.

CONCLUSIONS

Developing an interactive online modeling and visualization system to predict sonar-induced acoustic fields inside beaked whales as well as inside other marine mammals is a formidable task. It was the overarching goal of the project to effect this system, but it was not completed. However, the essential composition of this system was specified in detail, recognizing that it would be necessary to solve several tens of millions of equations simultaneously.

A synthetic model of Cuvier's beaked whale was developed based on CT scans of the head of a freshly dead Cuvier's beaked whale and CT scans of the body of a harbor porpoise. These data, in segmented form, are available from the Woods Hole Oceanographic Institution (WHOI) Computerized Scanning and Imaging (CSI) Facility website [http://csi.whoi.edu/].

Source literature reporting physical property values of cetacean tissues or closely related topics has been summarized.

Tourmaline sensors can be used to measure relatively weak, sub-shock acoustic pressures.

Sonar-induced acoustic pressure fields inside a common dolphin cadaver have been measured. Both amplitudes and times of flight have been measured.

Analytic models have been developed for benchmarking FEM code based on the interaction of plane harmonic pressure waves with lossy fluid and solid elastic spheres.

In the future, experimental measurements of sonar-induced acoustic fields inside instrumented marine mammal cadavers may be useful for investigating sound transmission pathways and for inferring acoustic properties of ensonfied tissues.

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