Mid-Frequency Sonar Interactions with Beaked Whales

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LONG-TERM GOALS

The top-level goal of this project is 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 is to acquire new high-resolution morphometric and physical-property data on beaked whales for use in the model. It is hoped that the availability of such a system, together with high-quality data, will give researchers insight into the nature of sonar interactions with beaked whales, and may prove useful in evaluating alternate sonar transmit signals that retain the required information content but with less effect.

OBJECTIVES

To achieve the long-term goals, a number of scientific and technological objectives have been identified. These include 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 carcasses, 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 AND WORK PLAN

The approach and work plan follow an integrated set of six tasks, which are briefly described.

Task 1. Development of a finite-element method to model acoustic interactions: This can be considered as a structural-acoustic problem, where most tissue groups and surrounding water behave as acoustic fluids and bony tissues behave as elastic solids. In the modeling, the beaked whale is a structure represented by its morphometry (Task 2), where each anatomical part is assigned its own set of physical properties (Task 3). This work is being performed by Co-PI Feijoo.

Task 2. Morphometry and meshing the three-dimensional anatomy: These data will be acquired principally from CT scans performed at the WHOI Computerized Scanning and Imaging (CSI) Facility. Image data on cetacean specimens will be expressed in Digital Imaging and Communications in Medicine (DICOM) format. Amira visualization software will be used for segmentation and surface reconstruction. Automatic mesh generation will employ tetrahedral elements. CT data will be provided by WHOI Senior Scientist D. Ketten. Co-PI Reidenberg will be responsible for interpreting the anatomical data. Co-PI Feijoo will construct finite-element meshes from the anatomical data.

Task 3. Physical properties of tissues: The best available data will 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. This task will be led by the PI, with potential contributions of new *in vivo* data from P. Rogers at the Georgia Institute of Technology.

Task 4. Measuring interactions of acoustic fields with cetacean carcasses: In order to test the FEM code (Task 1), measurements will be performed of the internal pressure fields in instrumented marine mammal carcasses. Carcasses will be prepared by surgically implanting acoustic sensors; CT-scanned to determine sensor location and morphometry; then acoustically measured at NSWC. D. Ketten will perform the surgery and CT-scanning. Co-PI Rye will lead the measurement work at NSWC.

Task 5. Testing the FEM model: Rigorous testing will be performed by comparison with analytic solutions for immersed simple objects.

Task 6. Virtual Beaked Whale: This interactive online modeling and visualization system is the principal deliverable of the project. It incorporates 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). The output will consist of computed solutions for the internal pressure and displacement fields (Task 1). The user interface is being recommended by Co-PI Hastings. Co-PI Feijoo will direct programmers in design and implementation sub-tasks. Co-PI Hastings will also perform testing and quality assurance. The PI will coordinate the various sub-tasks.

WORK COMPLETED

Task 2: The principal deliverable of the project, the Virtual Beaked Whale as described under Task 6, requires a morphometric model for a beaked whale. Potential sources of such data include gross anatomical measurements on a number of stranded beaked whales and computerized tomographic (CT) scans of the heads of a very few, different beaked whale specimens. Adult beaked whales are simply too large for ordinary CT-scanning. To remedy this shortcoming, a synthetic model has been developed based on the following sources of data: (i) head of a Cuvier's beaked whale (*Ziphius cavirostris*), a sub-adult male, total length 4 m, mass 730 kg, derived from a stranding on Cape Cod at Sandy Beach, Cohasset, MA, on 4 April 2006, with euthanization by the Cape Cod Stranding Network, delivery to WHOI for dissection, and head CT-scanned fresh on 5 April 2006 at WHOI, and (ii) body of a harbor porpoise (*Phocena phocena*), an adult male, length 105 cm, mass 22.1 kg, died naturally on 22 February 2010, found in Wellfleet, MA, delivered to WHOI by the International Fund for Animal Welfare (IFAW), and scanned fresh the following day, 23 February 2010, at WHOI. There is a presumption that the anatomy of the harbor porpoise body resembles that of a Cuvier's beaked whale, at least to within a scaling factor. The corresponding morphometric data were synthesized by reducing the head of the beaked whale specimen to the body of the harbor porpoise, rather than by enlarging the body of the harbor porpoise to the head of the beaked whale. More particularly, the head of the beaked whale was scaled and stitched to the body of the harbor porpoise within the Amira environment. Prior to modeling the sonar-induced fields, the synthetic beaked whale would be scaled to full beaked-whale size, of order 4-8 m in the present case of Cuvier's beaked whale.

Task 3: (1) Physical properties of beaked whale tissue: This continues to be discussed by the Co-PIs, with significant contributions and insight provided by D. Ketten. The basic problem is the lack of data, further exacerbated by the use of frozen and thawed tissue samples for the few measurements that have been undertaken for beaked whale tissue. This past year an unexpected source of direct, *ex situ* measurements on fresh tissue has been identified. This was a series of measurements of the longitudinal-wave sound speed performed by D. Chu and A. Lavery on tissue samples extracted from the freshly stranded Cuvier's beaked whale described above under Task 2. Measurements were performed with a unique apparatus (Chu and Wiebe 2005), which has earlier been applied to zooplankton (Chu et al. 2000, 2003, Wiebe et al. 2010). The measured beaked whale tissues included samples from the ventral, medial, and dorsal parts of the melon; blubber; fat; and muscle. The data were not completely analyzed following their collection on 6 April 2006, and have not been published. Permission has been granted by Chu and Lavery for the PI to analyze and otherwise make use of these data for present modeling purposes. (2) Gas volume conformational changes in beaked whales: The volume of gas contained within air spaces of a diving and ascending odontocete will vary depending upon depth, functional use, and compliance of the surrounding tissues. The dynamic relationship between gas volumes and ambient pressure is well understood, and can be used to make general assumptions about the total gas volume held within the whale at any depth relative to the total volume held at surface level. However, biological material is not uniform and therefore variations in compliance must be accounted for when examining pressure-volume relationships. The gas-containing organs can have a range of compliances depending upon the structure of the interstitial and surrounding tissues. Lungs, for example, are highly elastic, but have some stretch constraints related to their internal construction. The jointed ribs of odontocetes allow additional flexibility for lung collapse compared with terrestrial animals. The cartilage surrounding the larynx and trachea, particularly the complete circular rings found in whales, makes it stiffer than the lungs, but more pliant than the skull. Cranial bony sinuses are rigid and could crack under pressure changes if the ostia allowing gas exchange are insufficient or blocked. Odontocetes have thus evolved air sacs outside the skull that are free of the constraints of rigid bony walls. These air sacs are probably even more elastic than lungs, particularly as they have highly folded external contours and no tissues crossing through their lumen. At extreme depths, it is likely that these spaces collapse as they are completely evacuated of gas. Some species of deep diving beaked whales have evolved reduced or absent air sacs, probably through selection against these non-functional spaces at full collapse, which become liability for infections. There are several major functional conditions under which odontocete respiratory spaces may undergo conformational changes during a dive: breathing, sound production, hearing, and valsalva. It is clear that current knowledge of beaked whale anatomy is inadequate to predict gas volume conformational changes with depth and function. Work on such changes that is currently being performed at M. Moore's laboratory, with ONR support, is expected to be insightful.

Task 4: In the experiment performed on the instrumented carcass of a young adult male common dolphin (*Delphinus delphis*) at NSWC on 4 February 2009, sonar-induced internal fields were measured with tourmaline gages. These are more commonly used to measure high-amplitude, e.g., blast fields (Rogers 1997). However, they are evidently suitable for measuring low-amplitude, sub-shock fields too. During the experiment, the signals at the output of the gages were amplified by PCB 422 in-line preamplifiers, providing a voltage gain of 100. Earlier performance measurements of tourmaline gages have been refined and extended. In particular, two tourmaline gages together with the mentioned preamplifiers have been calibrated using a calibrated B&K 8103 laboratory hydrophone.

Task 5: Work designed for benchmarking computer code that solves the full-diffraction wave equation inside generally irregular and heterogeneous bodies has continued. The analytic solution has been generalized to the case of point sources in the nearfield of absorbing solid elastic spheres in a lossy fluid immersion medium. Tests have been performed using boundary-element and finite-element codes (Foote et al. 2009, 2010).

Task 6: (1) A substantial computing platform was acquired and configured to support the Virtual Beaked Whale. This is the HP ProLiant DL585 G6 server, with four six-core processors and four 500-GB SATA disks. (2) A user's guide for operating the Virtual Beaked Whale has been outlined.

RESULTS

The process of synthesizing a morphometric model of a beaked whale is illustrated in Figs. 1-3. It is emphasized that this is based on CT scans of the head of a Cuvier's beaked whale and body of a harbor porpoise, with scaling and stitching of the head to the body. Results of comparing the performance of a tourmaline gage used in the experiment with the instrumented common dolphin carcass on 4 February 2009 with that of a B&K 8103 calibrated hydrophone are shown in Fig. 4. Benchmark solutions for a particular sphere and frequency have been presented at meetings of the Acoustical Society of America (Foote et al. 2009, 2010).

IMPACT AND APPLICATIONS

National Security

At present, Navy operations at sea can be affected by the presence of marine mammals, hindering the use of sonar. The Virtual Beaked Whale will enable researchers to gauge the physical effects of particular sonar transmit signals on interactions with marine mammals.

Economic Development

Sonars, including echo sounders, are manufactured in the U.S. and in a number of other countries. Use of the Virtual Beaked Whale may suggest the value of using alternate transmit signal waveforms to mitigate possible harmful effects on marine mammals and other animals.

Quality of Life

An important tool in the assessment and management of fish stocks and ecosystems is acoustics. Safe operation of sonars and other active acoustic devices used in this work is essential. The Virtual Beaked Whale is expected to contribute to the process of ensuring safe acoustic operations.

Science Education and Communication

The new tool, the Virtual Beaked Whale, will be interactive. It is expected that the cumulative experience of users will contribute to new knowledge about acoustic interactions with marine mammals and other forms of aquatic life, also increasing public confidence in the value of data-based technology. The tool may be used by educators to promote education in fields as diverse as aquatic science, ecosystem assessment, resource conservation, and sonar engineering, also stimulating the kind of discussions that advance science.

RELATED PROJECTS

This project may benefit directly from a number of other projects. Three are cited. (1) Professor P. Rogers at Georgia Institute of Technology is currently investigating methods for determining elastic properties of cetacean head tissues *in vivo* under a grant from ONR. The quality of these will be unprecedented and of high value to the NOPP project. Discussions are underway with Rogers about measuring the properties of marine mammal tissues at the WHOI CSI Facility, mentioned under Task 3. (2) Dr. S. Ridgway of the U.S. Navy Marine Mammal Program and Dr. D. Houser of Biomimetica have provided morphometric data on a living bottlenose dolphin. (3) The Center for Ocean Sciences Education Excellence - New England (COSEE-NE) will be assisting the NOPP project in tailoring the interactive online tools under development to specific audiences. It will also be assisting in the dissemination of the results of the research and new educational tools.

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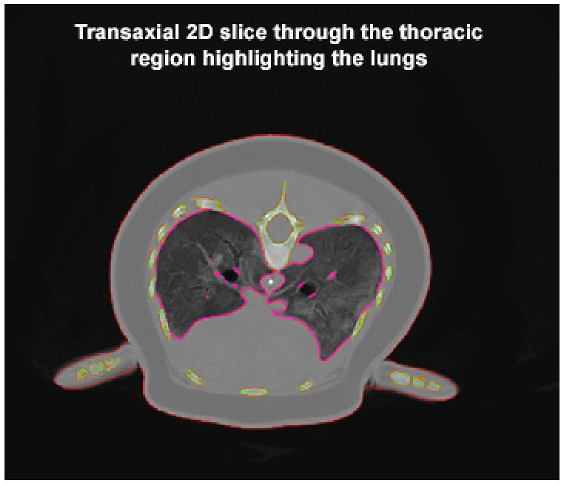

Fig. 1. Transaxial two-dimensional slice through the thoracic region of the synthetic model of a beaked whale, with lungs outlined in red, and skeleton, consisting of ribs, one vertebrate, and bones in the pectoral flippers, outlined in green. Credit: D. Ketten, S. Cramer.

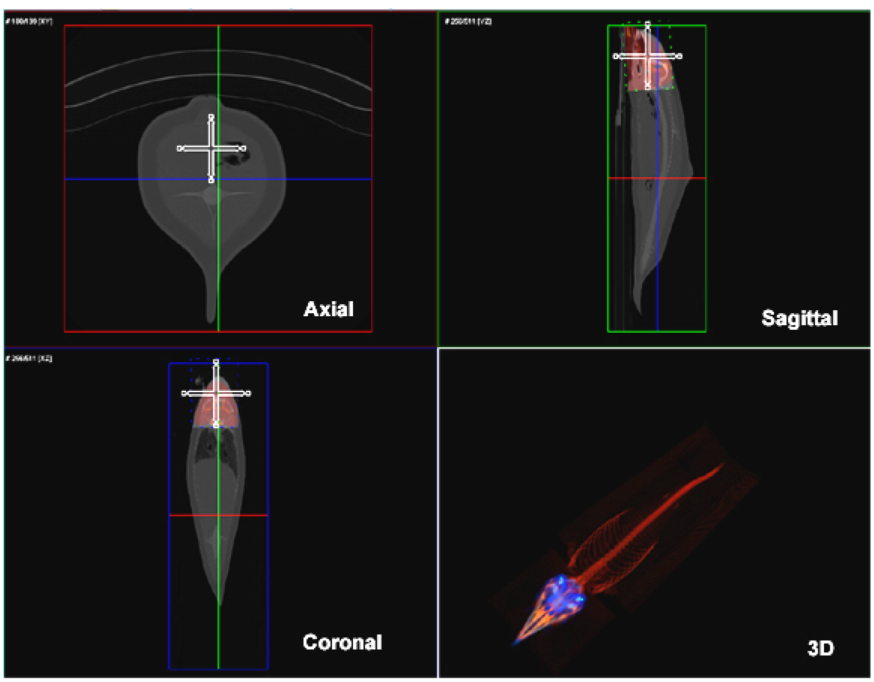

Fig. 2. Axial, sagittal, and coronal views of the synthetic model of a beaked whale, together with a dorsal transparent view highlighting the skeleton and air passages. Credit: D. Ketten, S. Cramer.

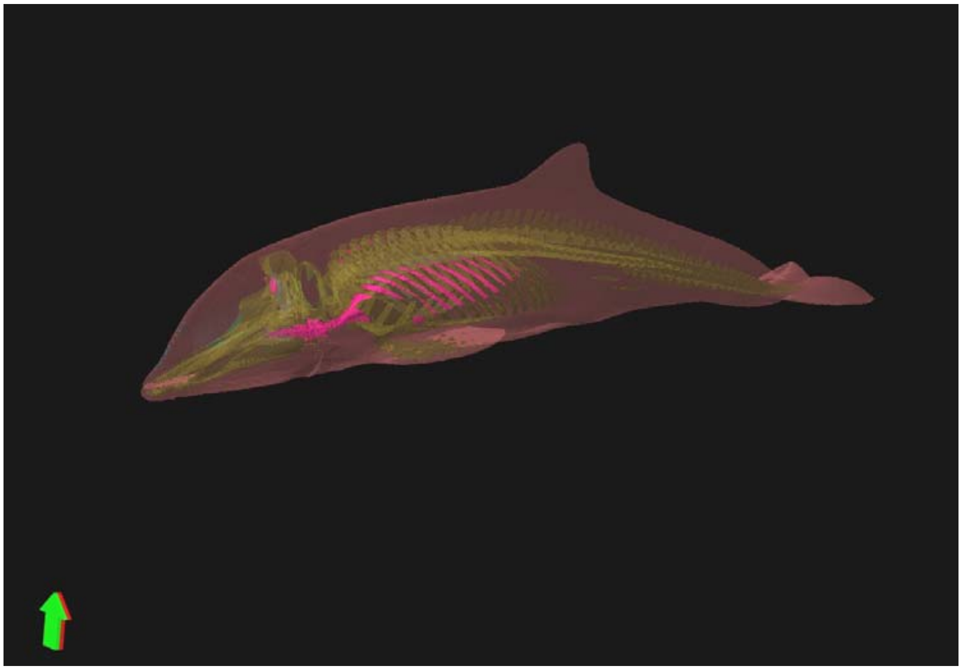

Fig. 3. Left lateral transparent view of the synthetic model of a beaked whale, highlighting the skeleton, air passages, and exterior surface. Credit: D. Ketten, S. Cramer.

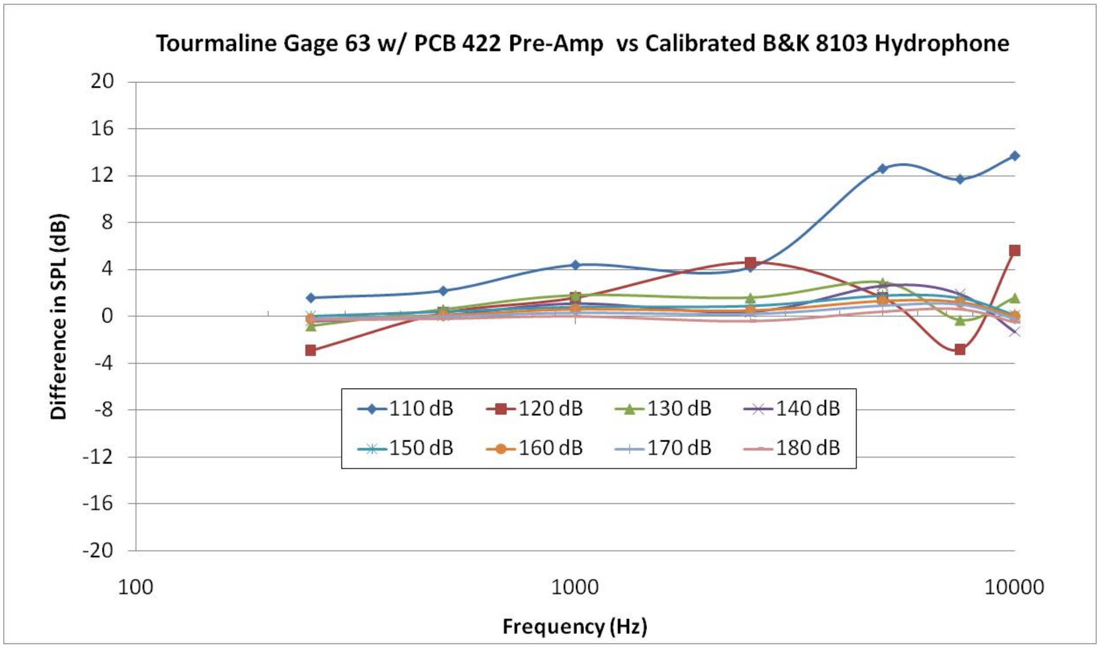

Fig. 4. Difference in output sound pressure level (SPL) between the pre-amplified tourmaline gage and calibrated B&K 8103 laboratory hydrophone. The legend indicates the calibrated sound pressure level, and the curves show the deviation from the calibrated level as a function of frequency. Each datum represents 100 averages of a 20-cycle tonal signal produced by a J11 underwater sound transducer. Measurements were made at frequencies of 250, 500, 1000, 2500, 5000, and 10,000 Hz. Credit: M. Hastings.