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. This will enable users to predict mid-frequency sonar-induced acoustic fields inside beaked whales and other marine mammals, as well as to evaluate effects of alternate signals. Another high-level goal is to collect 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 physical nature of sonar interactions with beaked whales.

OBJECTIVES

To achieve the long-term goals, a number of scientific and technological objectives have been identified. These include the following: To extend and apply existing computer codes, based on the finite-element method for acoustic interactions with structures, to beaked whales and mid-sonar frequencies in the range 1-10 kHz. To collect high-resolution morphometric data on beaked whales from *post-mortem* materials. To construct finite-element models of the anatomy, and to assign physical properties of tissues. To verify the finite-element code. To incorporate 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 are organized around an integrated set of six tasks.

Task 1. Development of a finite-element method to model acoustic interactions: The basic equations that govern acoustic interactions with structures will be solved for the case where the structure is a beaked whale as represented by its morphometry (Task 2), and where each part is assigned its respective set of physical properties (Task 3).

Task 2. Morphometry and meshing the three-dimensional anatomy: Morphometric data will be acquired from computerized tomography (CT) scans, visualized and labeled by tissue type, and represented by a finite-element mesh.

Task 3. Physical properties of tissues: The best available data, including both published and new data, will be used to represent the physically 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 carcasses: In order to test the finite-element code (Task 1), measurements will be performed of the internal fields in instrumented carcasses of marine mammals. Carcasses will be CT-scanned to determine the morphometry and location of surgically implanted sensors, then acoustically measured at the NSWC facility.

Task 5. Testing the FEM model: Rigorous testing will be performed by comparison with analytic and other solutions for acoustic interactions with 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). However, it also allows the user to enter other morphometric and physical-property data directly. The user will be able to specify an essentially arbitrary mid-frequency sonar signal. The output will consist of computed solutions for the internal field (Task 1) at user-specified locations.

WORK COMPLETED

On Task 1, the finite-element-method (FEM) code at the heart of the modeling system has been extended in several ways. (1) A perfectly matched layer has been implemented. (2) Frequency-domain elastic elements have been realized in code, allowing propagation of shear waves in addition to longitudinal acoustic waves in elastic tissues such as bone. (3) Interface elements have been added to transfer loads, namely pressure and stress, between acoustic and elastic elements. (4) A ten-node tetrahedral element was implemented in the code allowing for quadratic interpolation of basic fields.

On Task 2, work has been completed on several operations necessary for representing the animal model in a three-dimensional computational space. Anatomical realizations by Amira have been interfaced with the basic meshing software and FEM software. Meshing developments have been illustrated using morphometric data derived from CT scans at 8-mm-slice thickness on a 142-cm-long common dolphin specimen. Recently a new specimen, a 138-cm-long common dolphin, was CT-scanned at the WHOI CSI Facility at much higher resolution using 1-mm-thick slices. CT data on a living bottlenose dolphin have been received from the U.S. Navy Marine Mammal Program. Meshes generated from the first specimen are illustrated in Fig. 1. Images of tissues have also been identified by tissue group in an operation called labeling. In the case of the same 142-cm-long common dolphin, the lower respiratory tract and nearby tissues have been labeled in Fig. 2.

On Task 4, a series of tests have been performed on sensors to be used in the acoustic experiments with instrumented marine mammal carcasses at NSWC. These tests have established that tourmaline sensors typically used at shock-pressure levels can also be used at sub-shock levels, and that new Lenz-effect transducers can generate powerful acoustic signals in the upper part of the mid-frequency sonar band. Experience has been gained in configuring the facility for marine mammal carcasses through measurements performed at the same facility with a 30-kg pig carcass. This carcass has been instrumented through surgical implantation of tourmaline sensors, and used in acoustic tests in preparation for the marine mammal carcass experiments.

On Task 5, analytic solutions for the acoustic interaction of plane acoustic waves with an immersed, absorbing, fluid sphere have been developed and rendered in code for use in validating the FEM code. These solutions have been realized numerically (Foote 2007a,b, Foote and Francis 2008) for 50-mm-diameter spheres ensonified in water at 10 and 100 kHz. The sphere has been represented as a fluid with variable mass density over the range 500-2000 kg/m^3 to achieve density contrasts with water of 0.5-2, variable sound speed over 750-3000 m/s to achieve sound speed contrasts with water of 0.5-2, and variable absorption coefficient over 0-10 dB/wavelength. The pressure and displacement fields have been computed along the sphere axis, as defined by direction of propagation of the incident wave; transverse to this axis from center; and along the surface from the forward to reverse directions.

On Task 6, visualization routines were developed to return data from the FEM system and display these on a webpage. This system is operational in a pilot mode and is being used internally. A significant achievement is development of a client-server system that displays the computational results in the form of pressure fields in user-defined cross sections of the computational domain. The client-server system is responsible for passing data among the different components of the simulation environment, namely meshing, preprocessing, and FEM-analysis programs. The visualization system is presently based in Matlab, and is capable of operating with meshes of up to two million elements. A new, successor system will be capable of operating with meshes with more than 20 million elements. A user group composed of colleagues from the international bioacoustics community is being defined for testing the Virtual Beak Whale when in a more advanced state.

RESULTS

Some exemplary computations of sonar interactions with the 142-cm-long common dolphin are shown in Fig. 3 (Feijoo and Foote 2008). These results are preliminary, as the dolphin is represented as a structure capable of supporting longitudinal acoustic waves but not shear waves.

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. If the internal pressure or particle displacement at particular locations is found to be harmful, modifications to the sonar transmit signal waveform can be investigated quantitatively, enabling a mitigating measure to be evaluated.

Economic Development

Use of the Virtual Beaked Whale will enable alternate transmit signal waveforms to be investigated, possibly suggesting advantages to sonar manufacturers of using more complex waveforms.

Quality of Life

Ecosystem health is recognized to be important to the quality of everyday life, as expressed, for example, in consumer concerns about the effects of mercury and PCBs on fish as a food product. An important tool in the assessment and management of fish, as well as 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. (1) Professor P. Rogers at Georgia Institute of Technology is developing methods for determining elastic properties of cetacean head tissues *in vivo* under an ONR grant. The quality of these will be unprecedented. (2) Dr. S. Ridgway of the U.S. Navy Marine Mammal Program and Dr. D. Houser of Biomimetica are providing morphometric data on living dolphins. (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 and assisting in the dissemination of the results of the research.

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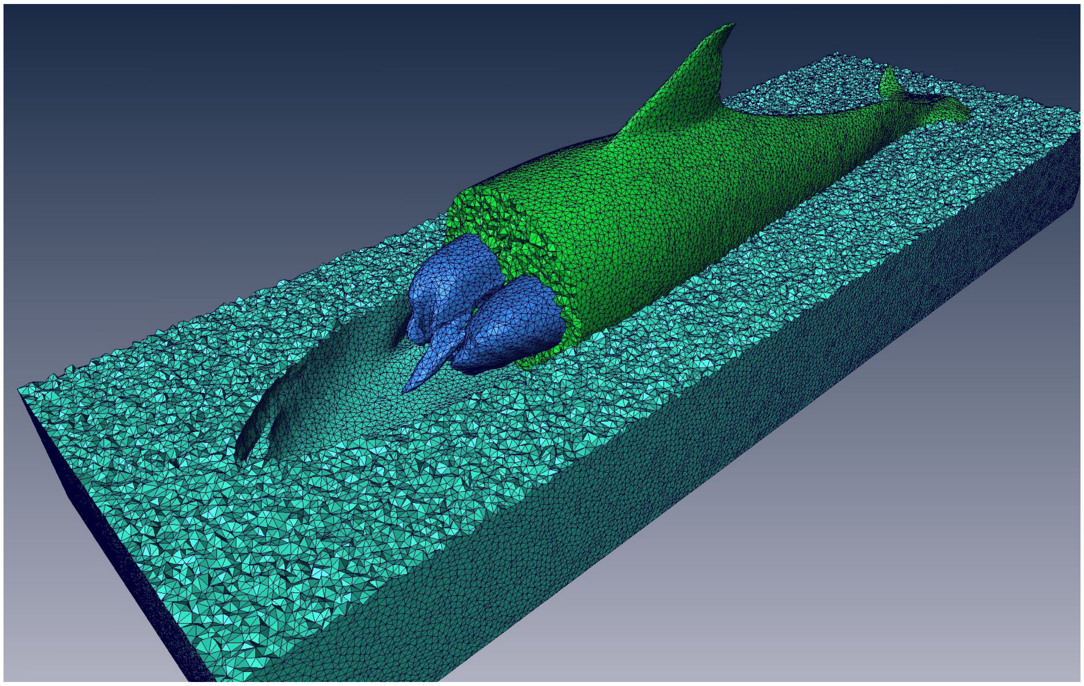

Fig. 1. Finite-element representation with tetraheda of a 142-cm-long common dolphin and external, computational volume. The lungs are indicated in blue.

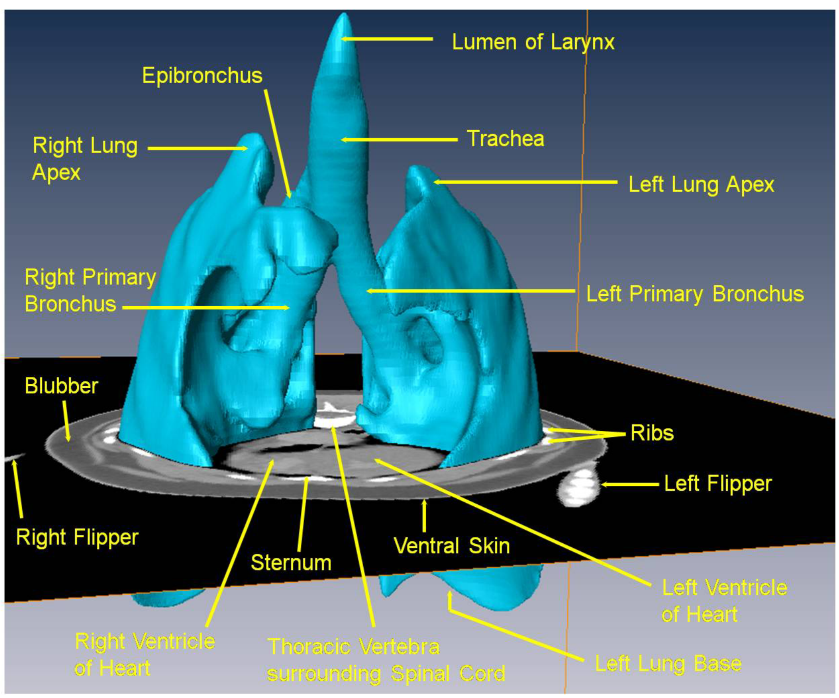

Fig. 2. Three-dimensional surface rendering, based on CT scans visualized with Amira, of the lower respiratory tract in a 142-cm-long common dolphin specimen, with superimposed transverse CT section and labeling of tissues.

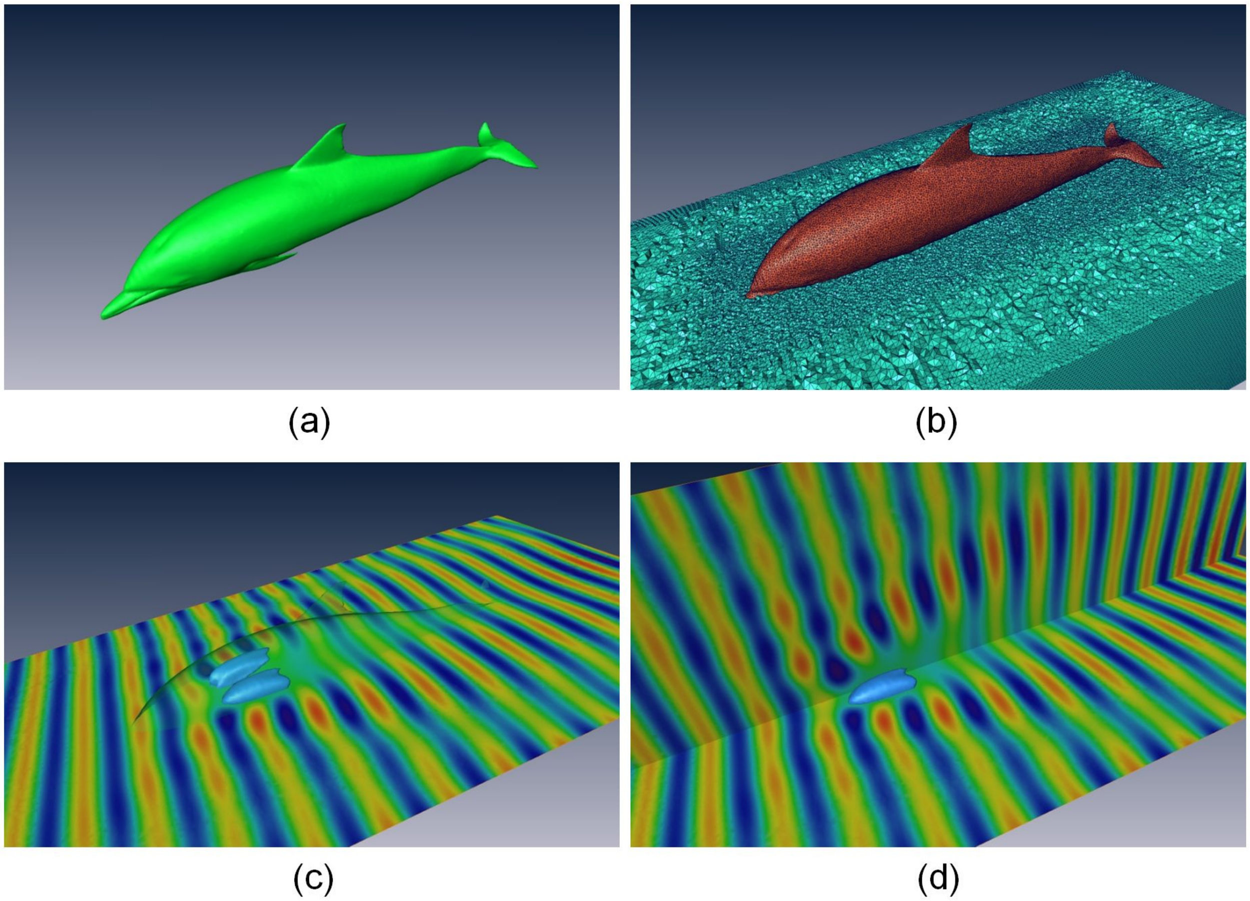

Fig. 3 Finite-element representation of a 142-cm-long common dolphin and simulation of the pressure field induced by a 10-kHz plane wave. (a) Volumetric rendering of the isolated animal, with skin in green. (b) Volumetric rendering of the animal, with skin in red, displayed in a cut of the meshed external volume. (c,d) Total pressure field due to a 10-kHz plane wave incident from the left along the axis of the animal, with lungs in blue.