

Virtual Experiments in Marine Bioacoustics: Whales, Fish, and Anthropogenic Sound

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LONG-TERM GOALS

This is a programmatic effort has three long-term goals. The **first** is to combine medical tomography (primarily CT-scans) with finite-element modeling software, and tissue property measurements, to simulate the bioacoustic interactions between selected anthropogenic sounds and fish anatomy. This method has already been successful in providing insights on such phenomena in some marine mammals (Cranford et al., 2008b; Cranford et al., 2008c). The **second** long-term goal is to improve and refine our ability to measure tissue samples by building a portable device that we can take into the field in order to measure physical properties from fresh tissue samples. The **third** and final goal is to continue the development of the finite element modeling software to incorporate new tools and techniques that will allow us to expand the taxonomic breadth of our vibro-acoustic research.

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OBJECTIVES

Our primary objective in the past year was to examine models of the otolith organs in an attempt to elucidate their pattern of motion in response to acoustic stimuli from different directions and at different stimulus frequencies (Krysl). The secondary objective was to standardize and improve our ability to measure tissue properties; primarily Bulk Modulus and sound speed in samples from various tissues (Shadwick). The tertiary objective was to refine the vibroacoustic toolkit (WHAC) and add more functionality.

APPROACH

We (Cranford and Schilt) have acquired postmortem specimens of the White Seabass (*Atractoscion nobilis*) from local sources (San Diego, CA), generated high-resolution CT-scans from these fish, and segmented various structures from the scanned volumes (e.g., see Figure 1).

Elucidating whether fish otolith organs analyze sound quality and in particular the role they play in enabling fish to discriminate between sounds of differing frequency, or sounds propagating from different directions, has proved elusive in the past.

In teleost fishes there are three pairs of otoliths, dense masses or stones of calcium carbonate sitting upon a patch of hair cells, each contained within a fluid filled sacs. Whether there is any peripheral analysis of sound quality by the otolith organ is still an open question.

It is necessary to account for the ability of fish to discriminate sounds of differing frequency (reviewed by Enger) (Enger, 1981). Sand has suggested that the movement patterns of the otoliths may be frequency dependent, and that the parts of the macula which are stimulated may depend upon frequency (Sand, 1974). Further studies are necessary before this suggestion can be confirmed.

There is also an issue over the determination of the direction of a sound source by fish. The ability of fish to discriminate sounds from different directions is clear, but the mechanism by which they achieve this has yet to be elucidated (see review by Sand and Bleckmann) (Sand and Bleckmann, 2008).

One of the obstacles standing in the way of better understanding of the mechanisms for determining sound direction and frequency discrimination is our lack of knowledge of the patterns of movement of the otoliths themselves. There is also an issue over whether the otoliths show a simple translation back and forth along the axis of the sound wave or whether the motion is more complex. Horner suggested that movement of the saccular otolith in a rostro-caudal direction in the cod was constrained by its positioning and attachment within the ear, and that it was only free to rotate or rock upon the macula (Horner, 1980).

In order to determine the effect that otolith shape might have on otolith motion, we (Krysl) ran two simulations using WHAC, our numerical analysis software. In the first simulation (Extracted Otoliths Simulation), we extracted the shapes of all six otoliths from high-resolution microCT scans of a single White Seabass. Those “otoliths” were assigned uniform calcareous material properties, immersed in a simulated shear-soft jelly, and exposed to different stimulus frequencies and directions.

In the second simulation (Simplified Otolith Simulations), we compared the responses of simplified otolith shapes with the results of the first simulation. In this second simulation, we used two simple shapes, a “spherical otolith” and a “hemispherical otolith.”

WORK COMPLETED

We have now examined two elementary models of “otoliths” (Extracted Otoliths Simulations & Simplified Otolith Simulations) in an attempt to elucidate their pattern of motion in response to planar harmonic waves from different directions and different stimulus frequencies.

Work on the development of new tools for the vibroacoustic software (WHAC) continues in Dr. Krysl’s lab at the University of California at San Diego. The newest tool provides the capacity to change the scale of element size during simulations within the model. This will allow us to reduce computational overhead for large, whole-animal data sets.

Dr. Robert Shadwick (University of British Columbia) continues his design work for the portable materials testing apparatus. This is an important component in our ongoing model-building process.

RESULTS

Extracted Otoliths Simulations

We collected high-resolution anatomic data from a small (21-cm total length) dead *Atractoscion nobilis* (Sciaenidae) from southern California by means of a micro-CT scanner (Figure 1). The scan data was used to extract high-fidelity representations of the otoliths and build a finite element model (FEM) by the methods and tools developed from Krysl et al. (Krysl et al., 2008) and Cranford et al. (Cranford et al., 2008a; Cranford et al., 2008c).

This was the basis of a simple FEM to investigate the dynamic response of fish otoliths to incident planar acoustic waves whose wavelengths are much longer than the dimensions of the otoliths. The otoliths are modeled as embedded in a shear-soft fluid-like jelly. The model does not currently include any other structures, such as the nearby cranial bones nor influences of the swimbladder. The model space was stimulated with two different sinusoidal signals (200 and 400 Hz) from several different directions with respect to the fish.

Figure 2 illustrates the shear forces that result from the relative motion between the otolith surfaces and the shear-soft jelly that surrounds them in the model space. These results show that the 400-Hz simulation produces greater shear values (due to larger displacements of the otoliths), particularly in the dorsoventral dimension, than does the 200-Hz signal of the same magnitude and direction. Similarly, Figure 3 shows that changing the direction of the acoustic stimulus also changes the patterns of shear forces acting upon the surfaces of the otoliths.

Even at this early stage of model development the FEM simulations produce informative results, suggesting that frequency and direction might be encoded by the unique rocking motions of the otoliths.

Simplified Otolith Simulations

The intriguing success of the Extracted Otolith Simulations catalyzed an investigation into whether simple otolith shapes would also produce intriguing results. In essence, do “spherical” or

“hemispherical” shapes produce angular oscillations due to torque in the presence of a relatively long wavelength acoustic stimulus? These simple shapes are abstractions of otoliths because they are without the distinctive shapes and sculpting found on actual otoliths, features often used as keys to species identification. In these Simplified Otolith Simulations we considered a progressive planar harmonic wave in an acoustic fluid with selected mass density, speed of sound, and frequency.

The acoustic wave impinges upon a very stiff homogeneous scatterer, the simplified otolith (which we may consider to be rigid) of arbitrary shape, whose characteristic dimensions are all much smaller than the wavelength of the incident acoustic wave.

In the case of a “spherical otolith,” we can demonstrate the intuitively obvious conclusion that uniform pressure across the symmetrical sphere in the acoustic fluid would not generate an acceleration or torque of the scatterer.

The case of the **hemispherical** “otolith” is different. There is a dynamic torque experienced by a hemispherical scatterer with the Cartesian coordinates origin located at the center of gravity. The numerical analysis indicates that the *X* and *Z* components of the torque are identically zero. However, the hemispherical scatterer rotationally oscillates about the *Y* axis (see Figure 4).

The motion of the hemispherical scatterer was investigated by numerical analysis using our vibroacoustic toolkit (WHAC). The upper part of Figure 4 shows the finite element model where individual voxels of the three-dimensional input image are converted to hexahedral finite elements (20-21 elements radially).

The lower half of Figure 4 shows the displacement in the *Z* direction of the two points *A* and *B* on the circular base of the hemisphere. Note that the two points are offset in the direction of the wave propagation. It is clear that the hemispherical scatterer rocks or wobbles since the two points displace with approximately opposite phase.

Furthermore, for a spherical scatterer all components of the dynamic acoustic torque would be identically zero (as expected). This can be readily extended to non-spherical shapes which nevertheless have three orthogonal planes of symmetry. It follows then, that for any 3D orthogonally symmetrical scatterer, the dynamic torque will be identically zero (i.e., no torque). Asymmetrical shapes, however, will experience a dynamic torque or rocking in accordance with the specific parameters and initial conditions.

IMPACT/APPLICATION

The Extracted Otolith Simulations and the Simplified Otolith Simulations produced similar “rocking” motions from unsymmetrical “otoliths.” This consistency hints at a potential principle of otolith motion that might be common to all teleost fish. Future iterations will include additional anatomic components within the model.

RELATED PROJECTS

This project is an outgrowth of the methodology we have developed over the past eight years (Cranford et al., 2010; Krysl et al., 2008; Krysl et al., 2006; Soldevilla et al., 2005). We are currently

using the same basic methods to study interaction between toothed whale anatomy and selected sounds.

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PUBLICATIONS

Cranford TW, Krysl P, Amundin M (2010) A New Acoustic portal into the Odontocete Ear and Vibrational Analysis of the Tympanoperiotic Complex. PLoS ONE 5:e11927

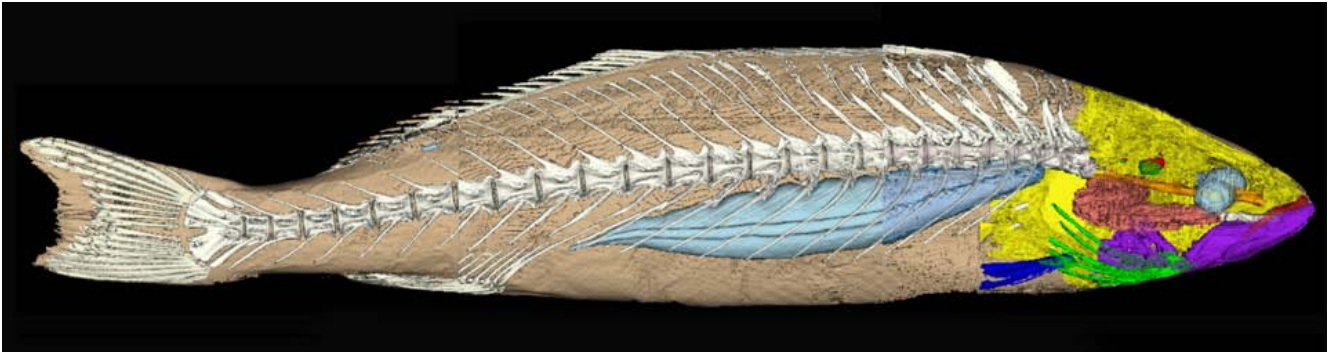


Figure 1 – White Seabass (*Atractoscion nobilis*) reconstructed from CT scans. Among structures visible in the image are: Vertebral column, swimbladder, skull, eyes, gills, jaws, other associated bony elements, and otoliths.

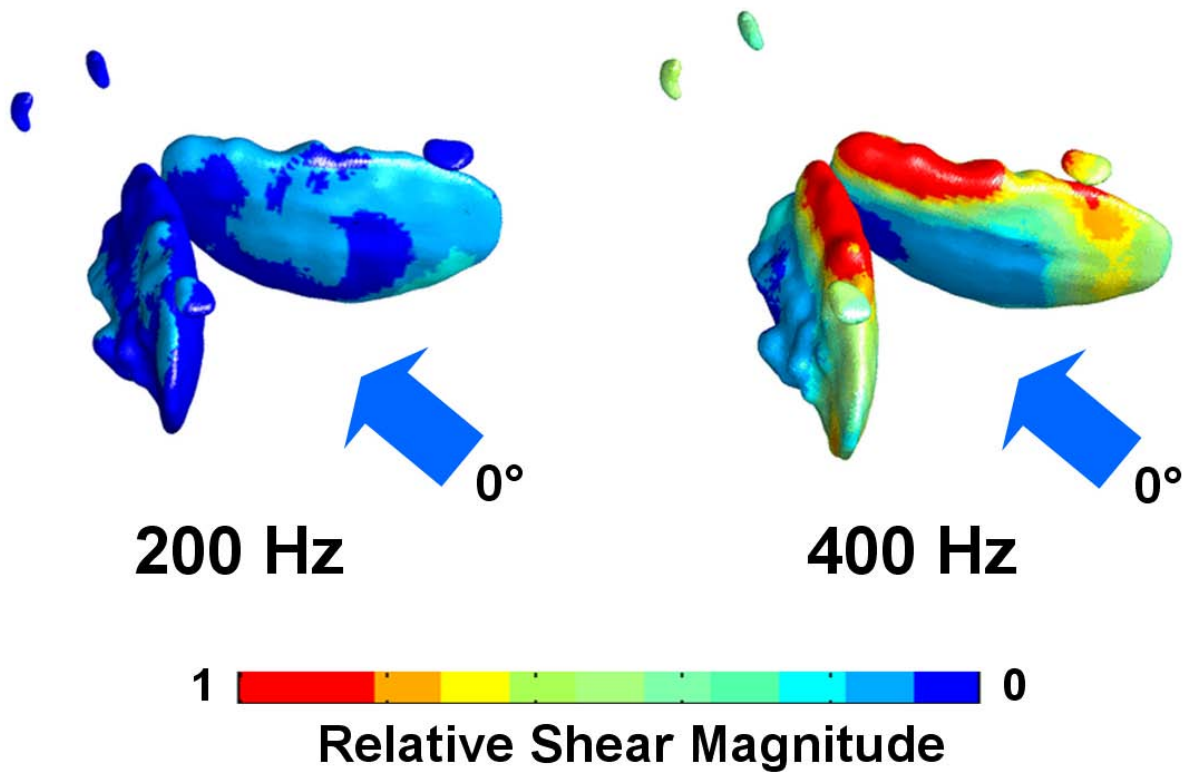


Figure 2 – A single instant in time for progressive planar harmonic sound waves that arrive from directly in front of the fish otoliths (angle of incidence = 0°) at each of two frequencies, 200 Hz and 400 Hz. Color variation indicates the magnitude of shear between the surfaces of the otoliths and the surrounding jelly-like material. The asymmetric shapes of the otoliths generate rocking motions when excited by sound.

One Stimulus Frequency and Amplitude from Three Angles of Incidence

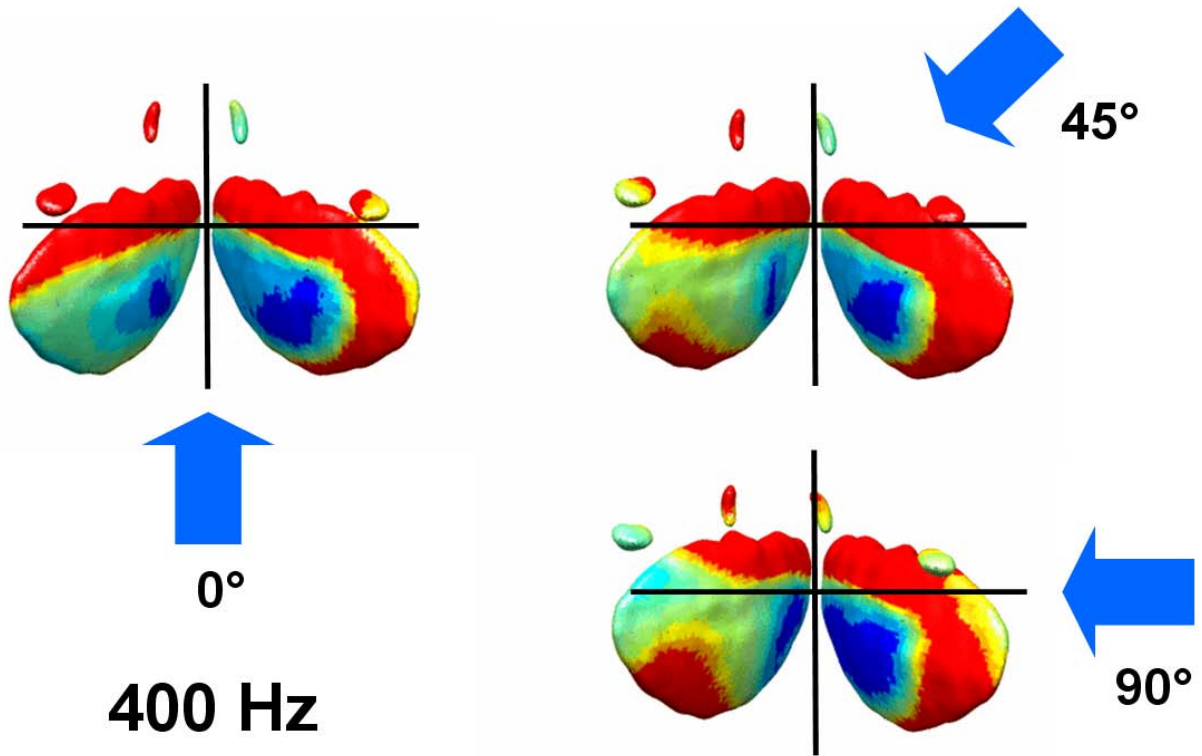


Figure 3 – FEM simulations of extracted otolith motion and magnitude of shear produced by the same stimulus frequency (400 Hz) from three different directions (0° , 45° , and 90°). Color variation indicates the magnitude of shear between the surfaces of the otoliths and the surrounding jelly-like material (the Relative Shear Magnitude scale the same as in Figure 2).

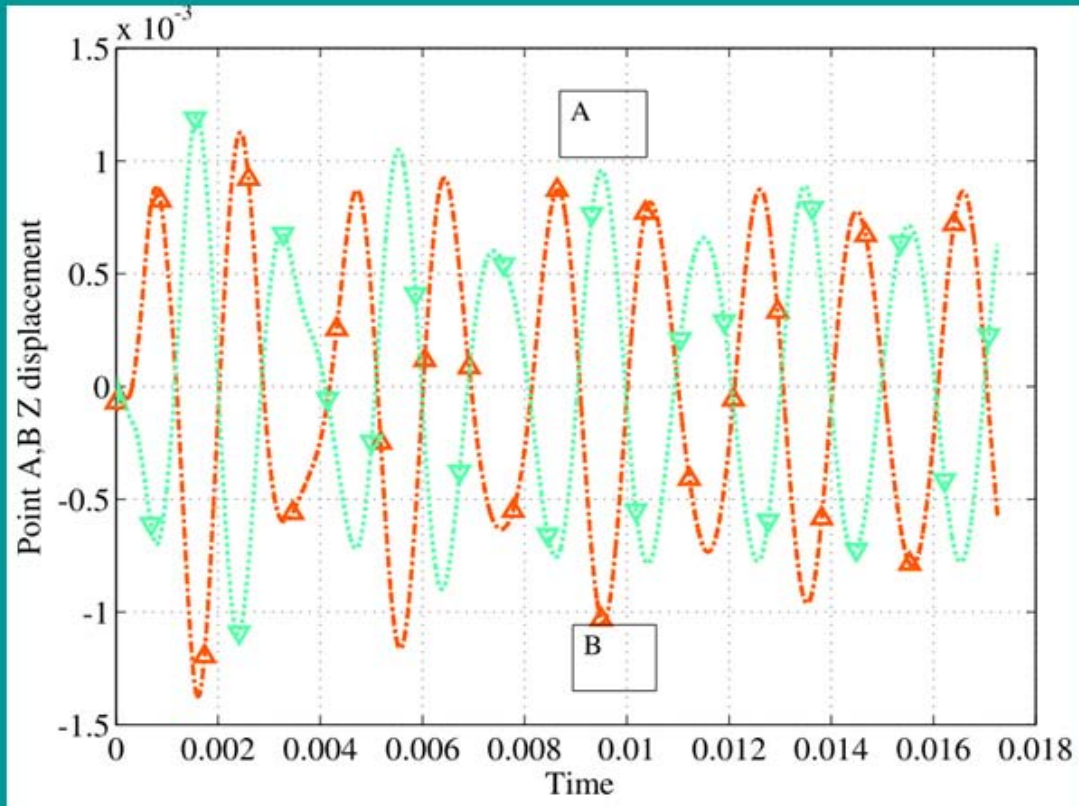
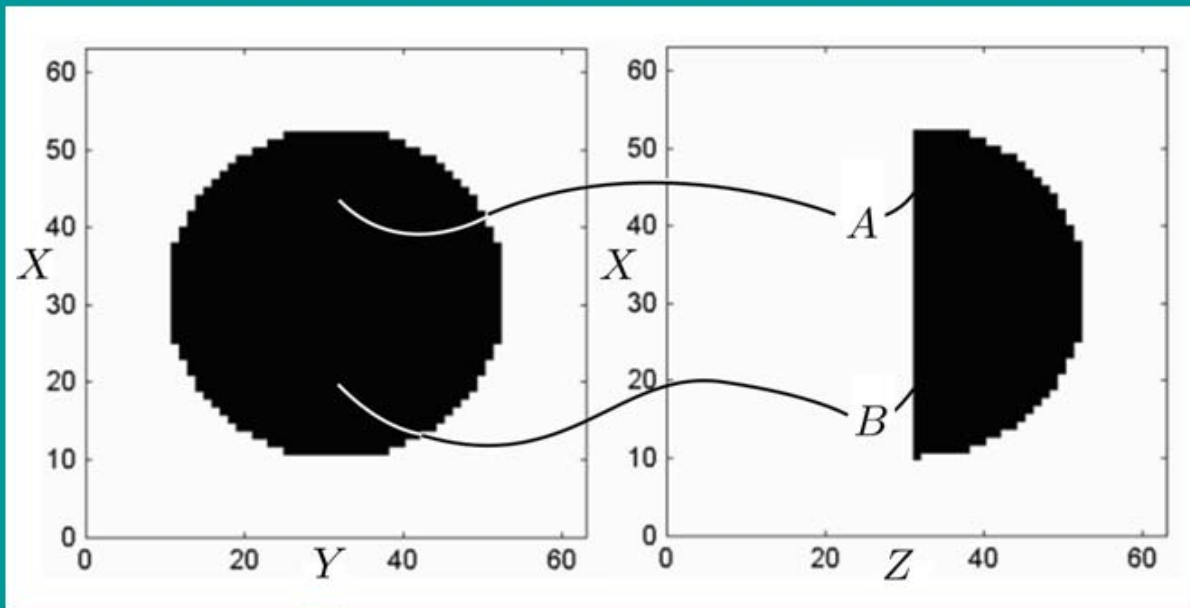


Figure 4 – The upper part of the figure shows a sketch of a simplified hemispherical “otolith” and designates two points (A and B) on its circular base. The lower part of the figure shows the displacement in the Z direction of the two points A and B through time during the simulation. Note that the two points are offset in the direction of the wave propagation. It is clear that the hemispherical scatterer rocks (wobbles) since the two points displace with approximately opposite phase. The difference between the two displacements divided by their distance in the X direction yields the approximate rotational angle.