UC San Diego
UC San Diego News Center

January 29, 2015

How Whales Hear: 3D Computer Simulations of Baleen Whale’s Head Point to Skull Vibrations

Researchers at San Diego State University and the University of California, San Diego, shed new light on how whales are able to hear, and more specifically on the role of the skulls of at least some baleen whales—fin whales to be precise.

In their study, published today in the journal PLOS One, marine biologist Ted W. Cranford of San Diego State and UC San Diego structural engineer Petr Krysl reveal that fin whale skulls have acoustic properties that conduct low frequencies directly into the marine mammals’ ear bones. The researchers digitally recreated in great detail the skull of a juvenile fin whale in order to run simulations that led to their findings—a first in computer simulation history.

Deformations and motion of the skull for 250 Hz incident wave. Amplitude magnified 20,000 times

Understanding how baleen whales hear has been a great mystery for marine mammal researchers. Baleen whales, also known as mysticetes, are the largest animals on earth, comprising such whales as blue whales, minke whales, right whales, gray whales and fin whales. These whales can emit extremely low frequency vocalizations that travel extraordinary distances underwater. The wavelengths of these calls can be longer than the bodies of the whales themselves. All of these whales are considered endangered, with the exception of the gray whale, which recently was removed from the endangered species list, Cranford said.

Over the past few years, government regulators have been attempting to enact laws placing limits on the amount of man-made noise that baleen whales can be exposed to. These man-made noises come primarily from three sources: commercial shipping, energy exploration and military exercises.

Motion of the tympanoperiotic complex for pressure loading at 1 kHz. (Animated visualization link with displacements magnified by 5,000 times).

According to Cranford, baleen whales might be particularly susceptible to negative effects from these sounds. Many of them produce vocalizations in the same frequency range as man-made noises, and too much man-made noise could limit the distance over which the whales are able to communicate about things like food and mates. Because low frequency sounds travel so far in the ocean, groups of whales that appear to be extremely far apart might indeed be within “hollerin’ distance,” as Cranford puts it.

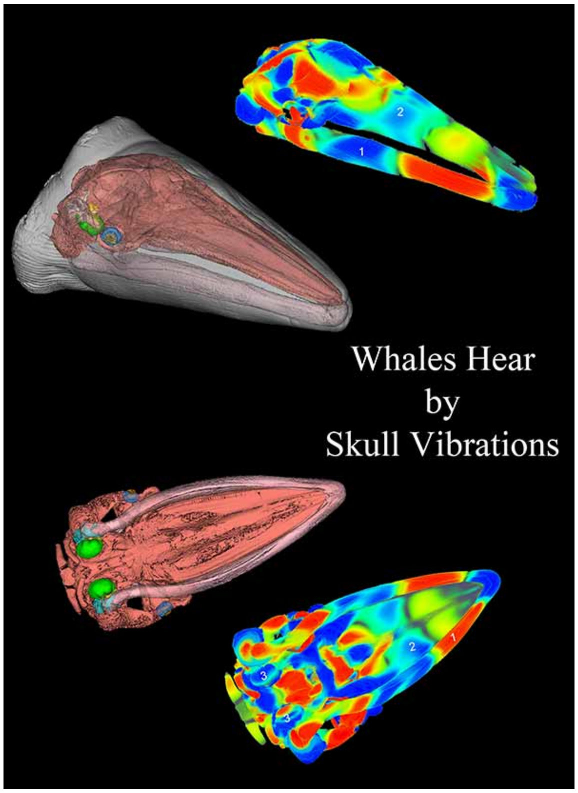
However, little information was available about how baleen whales actually hear for government regulators to base new legislation on. Most of what scientists know about how whales hear comes from inferring their frequency range from their own vocalizations, as well as anatomic studies of the ears and some sound playback experiments with whales in controlled environments.

Computer simulations

Cranford and Krysl wanted to take a different approach: build a highly complex three-dimensional computer model of a baleen whale head—including the skin, skull, eyes, ears, tongue, brain, muscles and jaws—and then simulate how sound would travel through it.

In 2003, they got their opportunity when a young fin whale beached on Sunset Beach in Orange County, California. Despite intensive efforts to save the whale, it died. Cranford and Krysl were able to obtain the animal’s head for their research and ran it through an X-ray CT scanner originally designed for rocket motors. The fin whale skull used for their experiment now resides in SDSU’s Museum of Biodiversity.

Once they had their scan, the researchers employed a technique known as finite element modeling that breaks up the data representing the skull and other parts of the head into millions of tiny elements and tracks their relationships with one another. The process was pretty much like dividing the whale’s head into a series of little Lego blocks where the properties of the materials (bone, muscle, etc.) determine the strength of the connection between the individual blocks. By simulating a sound wave passing through the computerized skull, they could see how each miniscule component of bone vibrates in response.



Four views of a fin whale skull. The top two images are anterolateral perspectives and the bottom two images are ventral views. The brightly colored images at the top and bottom show the deformation pattern as the skull bones interact with an oncoming 3 kHz underwater acoustic pressure wave. Number labels indicate anatomic structures: 1 is the mandible; 2 is the maxilla; 3 labels both tympanic bullae.

“At that point, computationally, it’s just a simple physics problem,” Cranford explained. “But it’s one that needs lots and lots of computational power. It can swamp most computers.”

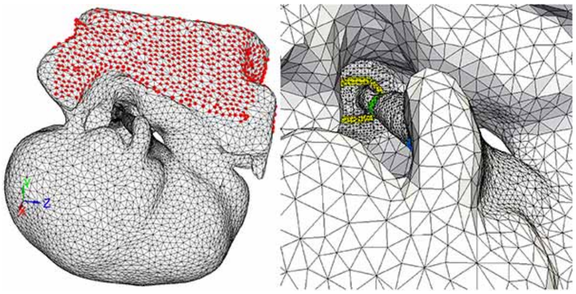
Krysl created the tools to run the simulations, based on his computational expertise and his knowledge of the mechanics and physics of the structures present in the whale’s head. The simulations showed that the long wave lengths whales use to communicate make their whole body vibrate, including the skull. As a result, the whale’s ear bones vibrate as well, creating a pumping motion in the mammals’ cochlea.

The scan was of a juvenile’s head, but researchers wanted to find out what would happen in an adult. So they took the data from the scan and recreated a head that was three times bigger. When they ran the simulations again, they discovered the same mechanism at work.

Krysl used a supercomputer in his own lab in the Structural and Materials Engineering building at UC San Diego, capable of running simulations with more than one billion unknowns. Some of the simulations ran for days and even weeks.

How whales hear

There are two ways sound can reach a whale’s tympanoperiotic complex (TPC), an “interlocking bony puzzle” of ear bones that is rigidly attached to the skull. One way is for the sound’s pressure waves to travel through the whale’s soft tissue to their TPC, but this becomes ineffective once sound waves are longer than the whale’s body, Cranford said.



(A) Finite element mesh 4 (approximately 41,000 nodes, 230,000 elements). (B) Close-up of the ossicular chain and the sigmoidal process in the foreground. The joints between the ossicles are shown in color.

The second way is for sounds to vibrate along the skull, a process known as bone conduction. Unlike pressure waves passing through soft tissue, longer waves lengths are amplified as they vibrate the skull.

When Cranford and Krysl modeled various wavelengths traveling through their computerized skull, they found that bone conduction was approximately four times more sensitive to low frequency sounds than the pressure mechanism. Importantly, their model predicts that for the lowest frequencies used by fin whales, 10 Hz – 130 Hz, bone conduction is up to 10 times more sensitive.

"Bone conduction is likely the predominant mechanism for hearing in fin whales and other baleen whales," Cranford said. "This is, in my opinion, a grand discovery."

Krysl added that we humans experience a version of this phenomenon, too.

"We have that experience when we submerge entirely in a pool," he said. "Our ears are useless, but we still hear something because our head shakes under the pushing and pulling of the sound waves carried by the water."

It's possible these new findings will help legislators decide on limits to oceanic man-made noise, but Cranford stressed that what's most important about their project is that they managed to solve a long-standing mystery about a highly inaccessible animal.

"What our contribution does is give us a window onto how the world's largest animals hear, by an odd mechanism no less," he said. "This research has driven home one beautiful principle: Anatomic structure is no accident. It is functional, and often beautifully designed by nature in unanticipated ways."

Future work

Cranford and Krysl have studied many species of toothed whales and beaked whales over the past 13 years, as well as dolphins. Their next step is to try to replicate the study for other species of baleen whales. Researchers will be reaching out to museums that house whale skulls. “There is a blueprint for multiple species and it is useful to compare across species to gain insight,” Krysl explained.

The researchers’ work would not have been possible without support from the Office of Naval Research (Code 32), sponsored by Dr. Michael J. Weise; the Office of the Chief of Naval Operations, Environmental Readiness Division (OPNAV N45), sponsored through the Living Marine Resources program by Dr. Frank Stone and Dr. Robert Gisiner; and X-ray CT scanning was conducted at Hill Air Force Base in Clearfield, Utah, in the Non-Destructive Inspection Missile Support Group. The latter facility is the only one large enough in the world to produce the data needed for this study.

MEDIA CONTACT

Ioana Patringenaru, 858-822-0899, ipatrin@ucsd.edu