Acoustic Scattering by Axisymmetric Finite-length Bodies with Application to Fish: Measurement and Modeling

by

D. Benjamin Reeder

B.S., Clemson University (1988)

Submitted to the Department of Ocean Engineering, MIT and the Department of Applied Ocean Physics and Engineering, WHOI in partial fulfillment of the requirements for the degree of

Doctor of Philosophy

at the

MASSACHUSETTS INSTITUTE OF TECHNOLOGY
AND THE
WOODS HOLE OCEANOGRAPHIC INSTITUTION

June 2002

Signature of Author ....
Department of Ocean Engineering, MIT and the
Department of Applied Ocean Physics and Engineering, WHOI
May 1, 2002

Certified by ....
Dr. Timothy K. Stanton
Senior Scientist, WHOI
Thesis Advisor

Certified by ....
Prof. Arthur B. Baggeroer
Professor, MIT
Academic Advisor

Accepted by ....
Michael S. Triantafyllou
Chair, Joint Committee for Applied Ocean Science and Engineering
Massachusetts Institute of Technology and the Woods Hole Oceanographic Institution

Acoustic Scattering by Axisymmetric Finite-length Bodies with Application to Fish: Measurement and Modeling

by

D. Benjamin Reeder

Submitted to the Department of Ocean Engineering, MIT and the
Department of Applied Ocean Physics and Engineering, WHOI
on May 1, 2002, in partial fulfillment of the
requirements for the degree of
Doctor of Philosophy

Abstract

This thesis investigates the complexities of acoustic scattering by finite bodies in general and by fish in particular through the development of an advanced acoustic scattering model and detailed laboratory acoustic measurements. A general acoustic scattering model is developed that is accurate and numerically efficient for a wide range of frequencies, angles of orientation, irregular axisymmetric shapes and boundary conditions. The model presented is an extension of a two-dimensional conformal mapping approach to scattering by irregular, finite-length bodies of revolution. An extensive series of broadband acoustic backscattering measurements has been conducted involving alewife fish (*Alosa pseudoharengus*), which are morphologically similar to the Atlantic herring (*Clupea harengus*). A greater-than-octave bandwidth (40-95 kHz), shaped, linearly swept, frequency modulated signal was used to insonify live, adult alewife that were tethered while being rotated in 1-degree increments over all angles of orientation in two planes of rotation (lateral and dorsal/ventral). Spectral analysis correlates frequency dependencies to morphology and orientation. Pulse compression processing temporally resolves multiple returns from each individual which show good correlation with size and orientation, and demonstrate that there exists more than one significant scattering feature in the animal. Imaging technologies used to exactly measure the morphology of the scattering features of fish include very high-resolution Phase Contrast X-rays (PCX) and Computerized Tomography (CT) scans, which are used for morphological evaluation and incorporation into the scattering model. Studies such as this one, which combine scattering models with high-resolution morphological information and high-quality laboratory data, are crucial to the quantitative use of acoustics in the ocean.

Thesis Advisor: Dr. Timothy K. Stanton
Title: Senior Scientist, WHOI

Academic Advisor: Prof. Arthur B. Baggeroer
Title: Professor, MIT

Acknowledgments

Science, as in life, is not conducted in a vacuum: this thesis is the result of contributions by many individuals, both directly and indirectly. Although it is impossible to recognize everyone who has had an impact on this research, I would like to recognize a few key individuals.

I am deeply grateful to the U.S. Navy, the Oceanographer of the Navy and the Office of Navy Research whose generous support made my participation in the Joint Program possible. I genuinely appreciate the guidance and support given to me by my thesis advisor, Dr. Tim Stanton, whose enthusiasm and energy for science is contagious. He was always available for discussion and questions, no matter how busy he was as Chair of the AOPE department at WHOI. I would also like to thank Prof. Arthur Baggeroer, for his advice and direction as my academic advisor at MIT, and for our many conversations about the Navy. Thanks also to the other members of my Thesis and Defense Committees: Dr. Ken Foote, Dr. Peter Wiebe and Dr. Jim Lynch, whose advice and comments regarding my research were greatly appreciated. I am indebted to Dr. Dezhang Chu for his many answers to my many questions regarding scattering theory, modeling and computing over the last five years. I would also like to thank Dr. Mike Jech for his involvement in the experimental portion of this research; Dr. Daniel T. DiPerna who proposed the scattering theory in Chapter 2 and provided much guidance during the course of this work; Dr. Trevor Francis of the University of Birmingham, UK, for generously providing the BEM calculation for Fig. 2-8; Falmouth Hospital for performing the CT scans of the alewife; Falmouth Animal Hospital for the use of their x-ray machine; Benthos, Inc. for the use of their test tank for the acoustic measurement portion of the study; Dr. Andrew Stevenson, Dr. D. Gao and Dr. Steve Wilkins at Australia's Commonwealth Scientific and Industrial Research Organisation (CSIRO), who have been very generous in their PCX imaging of the fish; and Dr. Hanu Singh, Dr. Andone Lavery and the Graphics Department at the Woods Hole Oceanographic Institution for help with image processing.

Words are inadequate to express my wholehearted thanks to my wife, Lisa, and my daughter, Emma, for their love, patience and support for me during the last five years. Their dedication and commitment to the success of this project were as crucial as my own. I would also like to thank my father, Max, for teaching me to value hard work and my mother, Jeanette, who inspired me to pursue science and engineering as a profession. Finally, I would like to thank God, who has given me this wonderful opportunity to study the physics of acoustic scattering, and without whom life and science would be meaningless.

Contents

---

[1]This chapter is based on an article submitted to the Journal of the Acoustical Society of America (Reeder and Stanton, submitted).

[2]This chapter is based on an article submitted to the Journal of the Acoustical Society of America (Reeder *et al.*, submitted).

Chapter 1

Introduction

1.1 Historical background for the use of sound in underwater observations

The first significant experiment in underwater acoustics was conducted by Colladon and Sturm in 1826 in the waters of Lake Geneva, Switzerland. By striking a bell underwater while simultaneously setting off a flash of light from explosives above the water, an observer in a boat some distance away measured the time lapse between the flash of light and the arrival of the sound of the ringing bell underwater. Colladon and Sturm, in a single experiment, not only a established a good value for the speed of sound (c) in fresh water but simultaneously, and possibly unintentionally, demonstrated the fact that as light and sight are the primary means of assessing the world above water, sound is the method of choice to observe the underwater world. Water is opaque to light but is transparent to sound which can travel great distances through the ocean and be detected at low frequencies even at megameter ranges (Baggeroer *et al.*, 1994).

Medwin and Clay (1998) opine that acoustical oceanography (the use of sound to study oceanographic processes) got its start in 1912, with the sinking of the HMS Titanic. Within months of the tragedy, patents were filed for new sonar systems to detect the presence of large objects underwater using acoustic backscattering. In fact, within 20 years of the Titanic's sinking, sonar was being used for the detection of schools of fish. Since that time, the science of underwater acoustics has progressed and has been applied in many ways to study the ocean environment. Much interest continues in the study of how human-generated sound interacts with marine organisms, whether for the purpose of understanding how the sound affects marine mammal behavior or for the purpose of detecting and tracking marine organisms. Acoustic scattering from marine organisms is the focus of much research by a diverse number of individuals: the academic biologist/acoustician, the commercial fisherman, the fisheries manager and the military sonar engineer.

1.2 Current interest in ocean observation

Just as in the 1930's, the modern commercial fisherman uses sonar to detect and localize the presence of schools of fish to maximize the catch. Given the limits on the number of fishing days and types of harvested fish allowed, remotely classifying fish would be advantageous for the commercial fisherman in order to avoid unnecessary catches of unwanted species and to maximize time at sea by limiting operational costs in terms of payroll and fuel.

The fisheries manager is tasked with observing and estimating fish populations in particular regions of the ocean to prevent over-fishing and the resultant collapse of the fisheries as happened in New England (Fogerty and Murawski, 1998; Steele, 1998), or worse, the extinction of particular species due to over-fishing or habitat destruction.

The academician is interested in better understanding the distribution, diversity, abundance and size distributions of fish populations in order to assess the state of the resources present in the ocean and changes in the environment in which these organisms live. Without knowledge of these factors, it is difficult to determine, much less predict, the effect on populations of low availability of food supplies for each species or the effect of over-fishing by humans.

The military sonar engineer is interested in observing and understanding how sound interacts with boundaries such as the sea surface, the seafloor, turbulence, internal waves, bubbles and marine organisms. Organism-based sound can be due to scattering from the animal or actually produced by the animal itself, e.g., whales, dolphins and snapping shrimp (Au and Banks, 1998; Olivieri and Glegg, 1998; Versluis *et al.*, 2000; Schmitz *et al.*, 2000). For active sonar systems seeking an acoustic target, organism-based interference contributes to the background reverberation detected by the sonar, decreasing the signal-to-noise ratio (SNR) and lowering the probability of detection (Urick, 1983).

1.3 Methods of ocean observation

Historically, scientists have relied on ocean surveys involving direct sampling with various types of nets to assess organism populations. Direct sampling furnishes biological data like abundance, biomass, length and species identification but is time-consuming and expensive. The catch may not be representative of the biomass in the water column since the net is selective, and as many marine organisms are free swimmers, the animals can avoid the net. Some delicate animals are destroyed by the nets, making it difficult to count the catch. The population estimate generated from the survey is susceptible to error since the sampling volume is small relative to the size of the region that is being surveyed. The abundance estimate from the small volume is then extrapolated to the whole, large region, causing errors to be propagated and amplified in the biomass estimate.

To overcome the problems and limitations plaguing the biological oceanographer and fisheries manager, the use of acoustic technology has made it possible to do rapid, high-resolution, broad-scale synoptic surveys of marine organisms (Gunderson, 1993). An acoustic survey would be less expensive by sampling the entire water column at a much faster rate, requiring less ship-time and labor while providing total coverage of the surveyed region. The acoustic survey is non-invasive, eliminating the problems of net avoidance and destruction of the organisms. The potential exists for the acoustic survey to produce high-resolution maps that can help advance understanding of aquatic community compositions, predator-prey interactions and habitat utilization (Horne, 1998).

Acoustic sampling produces acoustic data, not biological data; therefore, the acoustic backscattered signal must be translated into meaningful biological information. Abundance estimates using echo sounders have been made for several decades; however, these estimates are quite often based on the assumptions that (1) the aggregation is composed of animals of a single size and species, (2) the echo energy is proportional to the product of the number of animals per unit volume and average backscattering cross section, and (3) the average backscattering cross section is relatively constant for a given size and species, implying variations in echo energy are related to variation in numerical density. Directly relating acoustic scattering strength to biomass can be an unreliable indicator of abundance. The scattering strength of an organism depends upon the anatomical features of the animal, which vary widely between species that may even be of the same individual size or biomass, introducing large errors in the abundance estimates (Foote, 1980; Stanton *et al.*, 1994a). Dawson and Karp (1990) observed that fish at nearly horizontal aspect experienced approximately 10 dB target strength variations, apparently due to its swimming motion only. In an earlier study, Nakken and Olsen (1977) noted a 20 dB variation over time for a swimming Atlantic cod (*Gadus morhua*) at zero tilt angle.

Therefore, the goal of inverting acoustic scattering by marine organisms for meaningful biological information such as species, size and numerical density requires an understanding of the scattering characteristics of each type of organism. In other words, solving the inverse problem requires a detailed knowledge of the forward problem of predicting the acoustic scattering based on each animal's unique acoustic signature.

In the case of the impact of reverberation on the performance of military sonar systems, characterization of the complex reverberant properties of the water column has been largely ignored, i.e., the physics of the scattering by inhomogeneities, and specifically, marine organisms has not been taken into account in any significant way. Detailed physics-based characterization of marine organisms' scattering properties over a wide range of frequencies could lead to improvements in sonar system performance.

1.4 The physics of acoustic scattering

In order to exploit the properties of sound transmission and interaction with boundaries in the ocean, the physics of the scattering must be formalized and the factors affecting scattering studied in detail.

The far-field scattered sound wave is expressed as:

$$P^{scat} \underset{r\to\infty}{\longrightarrow} P_{inc}\frac{e^{ikr}}{r}f, \tag{1.1}$$

where P^{inc} is the pressure amplitude of the incident acoustic wave upon the object at a distance r away, k $(= 2\pi/\lambda, \lambda$ =wavelength) is the acoustic wavenumber of the incident field and f is the scattering amplitude. Given the dynamic range of the far-field scattering amplitude in the backscatter direction, it is often expressed in logarithmic terms as target strength (TS), expressed in units of decibels (dB) relative to 1 m (Urick, 1983):

$$TS = 10\log_{10}\sigma_{bs}, \tag{1.2}$$

where σ_{bs} is the differential backscattering cross section, which can be considered to be a measurement of the effective (acoustic) area of the target. The equation can be represented in another form:

$$TS = 20\log_{10}|f_{bs}|, \tag{1.3}$$

where f_{bs} is the backscattering amplitude and $\sigma_{bs} = |f_{bs}|^2$.

The scattering amplitude, f, is a complex function of the size, shape, orientation and material properties of the scatterer as well as the wavelength of the incident acoustic field. The scattering characteristics of the object are fully described by the scattering amplitude whose accurate parameterization is the focus of scattering physics research.

Prediction of an organism's scattering properties requires detailed, accurate measurement of the acoustic scattering characteristics of the animal of interest as well as a detailed theoretical scattering model to quantify the nature and extent to which size, shape, material properties, orientation and frequency affect scattering characteristics (Greenlaw and Johnson, 1983).

1.5 Overview of relevant work

Two vast bodies of literature exist on acoustic scattering that are nearly independent of each other: one consists of general scattering research without specific application,