Simulation of Bottom-interacting Ocean Acoustics:
Transition into New Applications

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LONG-TERM GOALS

The ability to accurately and efficiently model the sound field in the water column when there exists significant acoustic interaction with the seafloor is critical in a variety of ocean-acoustic applications. Simulation methods with detailed fundamental treatments of the effect of acoustic energy on an elastic solid are often insufficiently robust when the environment is complicated or when long ranges are desired. The goal of this research is the creation of stable and computationally inexpensive acoustic modeling methods that can accommodate range dependence in both the water column and the bathymetry, accurately portray bottom reflection even when it is substantially impacted by support for elastic shear conversion, and still reliably develop predictions at ranges as long as the basin scale.

OBJECTIVES

The objectives of the reported research can be summarized as follows.

- Improvements to the existing comparisons between equivalent-fluid simulations and benchmark models, and further investigation into which elastic media can be reliably depicted
- Examination of the performance of complex-density, equivalent-fluid methods in predicting acoustic characteristics of the data in the Basin Acoustic Seamount Scattering EXperiment (BASSEX)
- Application of these methods to computationally efficient, simplified geoacoustic inversions to provide estimates of bottom parameters
- Application of these methods to simulations of propagation in the horizontal direction from sources designed for geoacoustic exploration

APPROACH

Objectives of this research can be addressed through the use of “equivalent fluids” to represent the acoustic effects of the solid seafloor. Equivalent-fluid models are based on using effective parameters to mimic the reflection characteristics of an actual elastic solid. Simulations using equivalent fluids are more robust and computationally efficient than models that incorporate a thorough treatment of shear; they are useful when the sound field in the water is the quantity of interest. Prior uses of equivalent fluids were based on a calculation of an effective complex density to portray the impact of the seafloor (Zhang and Tindle, 1995) for low shear speed and grazing angle. In order to extend the validity to larger shear speeds and higher grazing angles, all of the parameters of the equivalent fluid are treated as free parameters in an attempt to accurately depict the elastic reflection coefficient.

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14. ABSTRACT

The ability to accurately and efficiently model the sound field in the water column when there exists significant acoustic interaction with the seafloor is critical in a variety of ocean-acoustic applications. Simulation methods with detailed fundamental treatments of the effect of acoustic energy on an elastic solid are often insufficiently robust when the environment is complicated or when long ranges are desired. The goal of this research is the creation of stable and computationally inexpensive acoustic modeling methods that can accommodate range dependence in both the water column and the bathymetry, accurately portray bottom reflection even when it is substantially impacted by support for elastic shear conversion, and still reliably develop predictions at ranges as long as the basin scale.

15. SUBJECT TERMS

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Preliminary efforts in the area of this research were motivated by the North Pacific Acoustic Laboratory (NPAL) experiment (Worcester and Spindel, 2005). A broadband acoustic source with a center frequency of 75 Hz was mounted on the seafloor near Kauai, Hawaii as part of this experimental effort. Because the source is bottom-mounted on a downslope, acoustic interaction with the seafloor affects the received field, even at long ranges. Additionally, the volcanic composition of the bottom material in this region suggests that the generation of elastic shear waves in the seafloor could be an important influence on the sound reflected back into the water column. Techniques for using an equivalent fluid to represent the seafloor were developed that enable efficient modeling of the impact of elastic shear on the sound field in the water. Near-source bottom interaction was characterized sufficiently for an unambiguous identification between arrivals in the data and in simulations at basin-scale ranges (Vera *et al*., 2005). An equivalent fluid was constructed based upon a presumed set of geoacoustic parameters that were treated as known.

The degrees of freedom represented by the selection of an effective compressional (sound) speed and complex density enable a “fit” to an elastic reflection coefficient resulting from parameters that are known *a priori*. Equivalent-fluid representations of the bottom can also be used in a procedure to estimate elastic parameters that are treated as unknown. Since models using an equivalent-fluid bottom are computationally straightforward, simulated acoustic fields using a range of parameters for the effective compressional speed and complex density can be executed practically for a variety of ranges of potential interest. Then, these model results can be compared to an experimental reception and the equivalent fluid that best represents the experimental effect of the elastic seafloor can be determined. Finally, the best equivalent-fluid simulation can be used to estimate the actual parameters of the seafloor solid based upon the degree of correspondence between the reflection coefficients of the given equivalent fluid and a set of elastic parameters.

This method of inverting for geoacoustic parameters by employing equivalent-fluid representations of the solid can be applied to data from the BASSEX experiment. During the BASSEX experiment, the NPAL Kauai source was recorded on ONR’s Five-Octave Research Array. Because of the portability of the receiver, receptions were recorded at a variety of azimuthal directions and relatively short ranges from a few to a few hundred kilometers. The accuracy of the equivalent-fluid representation can then be examined at ranges other than the one used to identify the complex-density parameters. Processed data for these purposes has been supplied by Dr. Kevin Heaney of Ocean Acoustical Services and Information Systems.

These modeling methods can be adapted to different types of experiments. A scenario of particular interest involves airgun array sources. These experiments are designed to provide highly accurate, detailed characterizations of the seafloor based on the direct return. However, significant amounts of acoustic energy can propagate in the horizontal direction out to long ranges. Simulations using an equivalent fluid could depict this energy effectively; the need to model the propagation on a fine grid of azimuthal directions could be addressed efficiently and reliably with these techniques. These efforts would represent a substantial improvement to current models, typically with only a single *2D* environmental slice, no treatment of shear in the bottom, and a simplified treatment of the source output (DeRuiter *et al.*, 2006). Collaborative discussions have begun with Dr. James Stephens, also of the University of Southern Mississippi, on the acoustic output of airgun arrays and deployments in the Gulf of Mexico. A systematic modeling effort to determine the far field of such sources in all horizontal directions would be valuable in, for example, quantifying and examining possible concerns over marine mammal exposure.

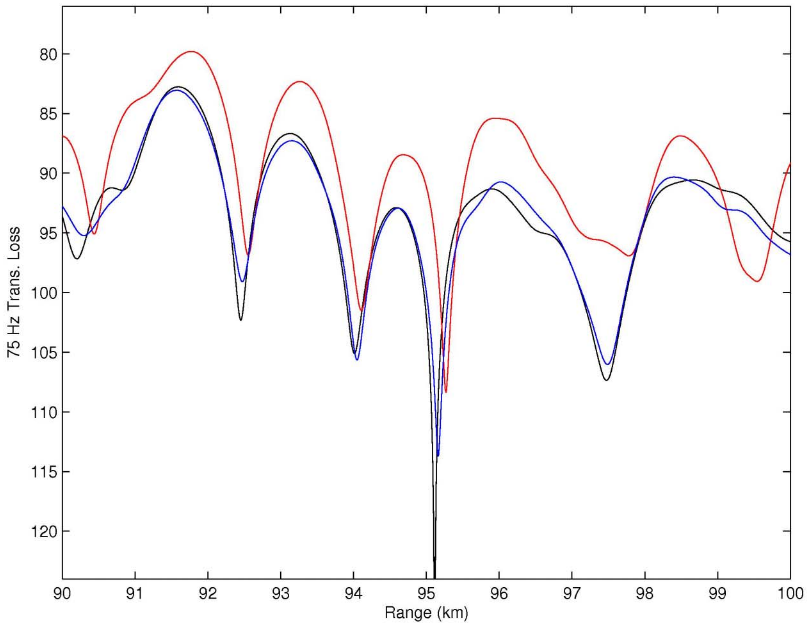

Figure 1: The single-frequency transmission loss as a function of range from a combined elastic-acoustic simulation is shown as a black line. An equivalent fluid determined according to previous techniques yields the red curve. The use of an equivalent fluid with parameters based on reflection coefficient correspondence results in the blue line and agrees more closely with the benchmark.

WORK COMPLETED

The accuracy with which equivalent-fluid models can reproduce the results of combined elastic-acoustic simulations was investigated. Propagation over several benchmark seafloor geometries, as well as experimental bathymetry from the NPAL project, was simulated with a range of parameters including ones in which shear was a significant contributor to acoustic losses. On the basis of single-frequency transmission loss at 75 Hz, it was found that the use of equivalent fluids generated by fits to the elastic reflection coefficient corresponded to elastic-acoustic simulations to within a few dB, even with highly variable seafloor depths and materials whose impact was dominated by shear conversion.

A reception at a range of 3.59 km was selected from the BASSEX data and used as the basis for determining an equivalent fluid that successfully replicated the influence of the actual seafloor. Bottom parameters tested included 16 values of the compressional speed (from 1000 to 4000 m/s), and 14 values each for the real and imaginary parts of the effective density (from 200 to 2800 kg/m^3) for a total of 3136 cases. Techniques for selecting a simulation that corresponded to the experimental result, as well as for identifying a set of elastic parameters with an acoustic effect similar to the selected equivalent fluid, were developed and implemented. The selected equivalent fluid was also used to simulate propagation to other ranges for which experimental receptions were available.

RESULTS

Equivalent fluids with all parameters determined by correspondence with an elastic reflection coefficient have been shown to provide more accurate models than those generated by selecting only a complex density in the limit of low grazing angle (Zhang and Tindle, 1995). Even for seafloor materials with substantial shear-dominated acoustic losses, an equivalent fluid can provide an effective simulation. A variety of such test cases have been considered. One of the most striking examples, and one of the earliest attempted, corresponds to propagation along one of the source-receiver paths in the NPAL experiment (Worcester and Spindel, 2005). Acoustic propagation was simulated from the bottom-mounted 75-Hz NPAL source near Kauai, Hawaii. The bottom material was a model for certain volcanic basalts (with a sound speed of 2200 m/s and a shear speed of 1100 m/s). The transmission loss comparison is shown in Figure 1. The expanded technique is clearly more accurate than the method of Zhang and Tindle. These tests, and other similar comparisons, have shown that the new equivalent-fluid method can accurately depict seafloor materials with high shear speeds; in fact, the limiting factor on the performance of the method appears to be the size of the relevant grazing-angle interval.

This project has also demonstrated the utility of equivalent fluids in inverting for geoacoustic properties that are treated as unknown. A reception from the BASSEX data selected for this analysis is shown in Figure 2; the range is 3.59 km and the receiver depth is about 260 m. The time series consists of a pronounced arrival between 2.4 and 2.6 s. Based on a comparison with ray calculations, the relevant trajectories for this arrival include both non-bottom-interacting paths and paths that reflect from the bottom near the source. The sound arriving at travel times between 3.0 and 3.4 s, with a level roughly 15 dB less than the earlier arrival, corresponds only to rays which have reflected from the bottom. In order to more directly address the effect of bottom interaction, this reflected arrival was used in the comparison between simulation and experiment.

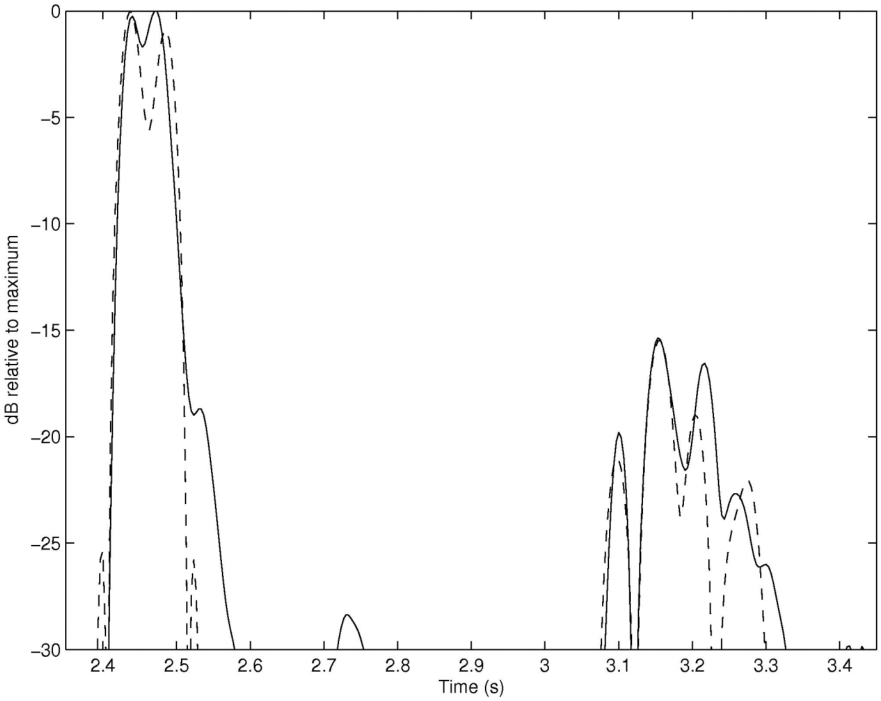

Figure 2: The received level data from a BASSEX reception at a range of 3.59 km is shown as a solid line. The set of equivalent-fluid parameters that were found to correspond most closely to the data yielded the simulated level shown as a dashed line.

Parabolic-equation simulations (Collins, 1993) of the 3.59-km propagation were performed for a range of different complex-density equivalent fluids. The simulation results were compared to the received level data based on the cost function

$$C_A = \frac{1}{N_i}\sum_{t_i} | D(t_i) - S(t_i) |$$

where t_i are the times for which the simulated level S(t) exceeded -30 dB below maximum, $D(t_i)$ and $S(t_i)$ are the data and simulation levels in dB, and N_i is the number of included values. The smallest value of C_A was found for a compressional speed of 4000 m/s and an effective complex density of 400+1200i kg/m^3. The data and simulation results are shown in Figure 2. This equivalent fluid was subsequently used to successfully model receptions at longer ranges (11.5 and 21 km).

The best equivalent-fluid simulation can then be used to estimate the actual elastic parameters of the seafloor solid. The degree of correspondence between an elastic solid and the identified equivalent fluid was based on the cost function

$$C_V = \frac{1}{M_i}\sum_{\theta_i} \frac{| L_{es}(\theta_i) - L_{ef}(\theta_i) |}{| L_{es}(\theta_i) |}$$

where θ_i are a set of angles spanning the relevant grazing-angle interval, M_i is the number of such angles, and $L_{es}(\theta)$and $L_{ef}(\theta)$ are the bottom loss for the elastic solid and the equivalent fluid. The elastic parameters that minimized C_V are a density of 1500 kg/m^3, a compressional speed of 2700 m/s and a shear speed of 1500 m/s. This solid is also roughly comparable to an initial estimate made for the elastic parameters in this area (a density of 2100 kg/m^3, a compressional speed of 2200 m/s and a shear speed of 1100 m/s) (Vera *et al*., 2005). The ability of these simulations to portray the experimental propagation indicates the utility of equivalent-fluid techniques and, with the relatively large shear-speed estimates resulting from the process, the need to consider elastic shear in explaining the loss observed in reflected arrivals.

IMPACT/APPLICATIONS

The ability to accurately simulate acoustic interaction with the seafloor is necessary in several different types of propagation scenarios. Support in the bottom material for shear waves can impact (or even dominate) the losses incurred upon reflection. Modeling the conversion of acoustic energy into elastic modes based on fundamental principles using combined elastic-acoustic algorithms is computationally demanding and can be numerically unstable, particularly for highly range-dependent, long-range transmissions. Since the loss due to shear is incorporated into the properties of a complex-density fluid, simulations using equivalent fluids are computationally inexpensive and stable.

This numerical performance was critical in successfully simulating basin-scale transmissions from the Kauai source in the NPAL experiment (Vera *et al*., 2005). These models were required to accommodate a broadband source mounted upon shear-supporting volcanic basalt and portray propagation for several thousand kilometers. Though the resulting simulations enabled an unambiguous identification of the data receptions, the accuracy of the method was not known precisely at that time. The present results indicate that equivalent fluids can be used to effectively represent the sound reflected back into the water column, even for strongly shear-supporting materials, a broad range of frequencies and/or very long ranges. These methods can be successfully employed whenever the sound field in the water column is the quantity of interest and the effect of the seafloor can be represented in terms of reflection. The efficiency and accuracy of the method for a broad range of bottom materials suggests that future applications in modeling lateral propagation from airgun arrays are likely to be successful.

RELATED PROJECTS

Dr. Arthur Baggeroer and Dr. Kevin Heaney have made it possible to use data from the BASSEX experiment and are supported by ONR Code 321OA.

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