Proceedings of Meetings on Acoustics

Volume 2, 2008 http://asa.aip.org

154th Meeting
Acoustical Society of America
New Orleans, Louisiana
27 November - 1 December 2007
Session 1aAO: Acoustical Oceanography

1aAO3. Complex-density, equivalent-fluid modeling of acoustic interaction with the seafloor

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Acoustic interaction with the seafloor can generate both compressional and elastic shear waves in the solid. Accurate models of shear propagation are often computationally expensive and difficult to apply to long-range propagation. When the sound field in the water is of primary interest, an equivalent-fluid model of the seafloor, with parameters chosen to match the reflection coefficient of the actual elastic solid, can sufficiently characterize the effect of the bottom on energy in the water. The effective density of the seafloor material in this approach can be a complex number. Prior methods for generating equivalent fluids were intended for low shear speeds and low grazing angles. Recent developments in the technique were intended to extend its validity to higher shear speeds and a wider range of angles. These efforts were initially motivated by the need to simulate bottom-interacting arrivals for the broadband Kauai source in the North Pacific Acoustic Laboratory experiment at megameter ranges. The work to be presented involves a more detailed examination of the performance of the method, including comparisons to benchmark models and to shorter range data from this Kauai source collected as part of the Basin Acoustic Seamount Scattering Experiment.

Published by the Acoustical Society of America through the American Institute of Physics

 [DOI: 10.1121/1.2907521]
Received 29 Feb 2008; published 9 Apr 2008

Complex-density, equivalent-fluid modeling of acoustic interaction with the seafloor

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PACS: 43.30.Zk, 43.30.Ma

1. INTRODUCTION

The level of sophistication required to successfully model acoustic interaction with the seafloor depends upon the particular transmission. For long-range experiments, the bottom can typically be modeled very simply if it is nearly flat and much deeper than the minimum sound speed. However, it is often desirable that acoustic sources or receivers be mounted on the seafloor, or located in relatively shallow regions. A more sophisticated treatment of the seafloor is necessary to successfully simulate these experiments.

The focus of the research discussed below is 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 the 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 for low shear speed and grazing angle.[1] 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.

Preliminary efforts in the area of this research were motivated by the North Pacific Acoustic Laboratory (NPAL) experiment.[2] A broadband acoustic source located on the seafloor near Kauai, Hawaii with a center frequency of 75 Hz and a two-dimensional receiver array oriented transverse to the propagation path are among the components of the NPAL network. The two-dimensional receiver array, located at a range of approximately 3900 km, provides the unusual opportunity for detailed experimental measurements of the horizontal, cross-range coherence of the acoustic signal. Efforts to compare horizontal coherence from the data, from broadband parabolic-equation simulations, and from analytic approximations to the acoustic path integral are ongoing; a comparison between different numerical models has been performed.[3] Because the source is bottom-mounted on a downslope, acoustic interaction with the seafloor affects the received field, even at long ranges. As shown in Figure 1, there exist ray trajectories which interact with the bottom only a small number of times near the source, and therefore can still be detected at long ranges. 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.[4]

2. EQUIVALENT-FLUID MODELING

The computational efficiency and robustness of an acoustic propagation model can often be improved by simplifying the treatment of acoustic interaction with the bathymetry. If the purpose of the model is to depict the sound field in the water column, then only the reflected wave is of interest and detailed modeling of shear propagation within the elastic seafloor can be avoided. For an acoustic wave propagating in the water, incident on an elastic solid seafloor, the complex reflection coefficient can be stated as:

$$V(k) = \frac{\gamma_1 P(k)\frac{\rho_2}{\rho_1} - i\eta_2}{\gamma_1 P(k)\frac{\rho_2}{\rho_1} + i\eta_2} \qquad (1)$$

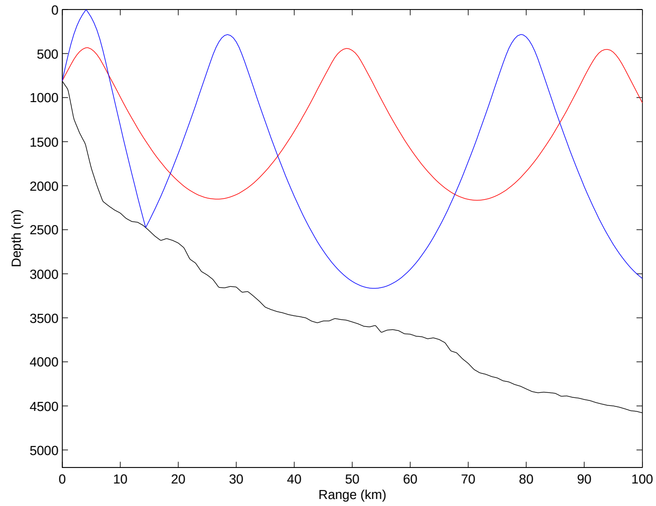

FIGURE 1. Sample rays are shown from the acoustic source near Kauai, Hawaii. The red ray is purely refracted. The blue ray reflects from the surface and the bottom. Because of the seafloor geometry, this bottom reflection occurs only once for this ray. Since the bottom loss that occurs for reflection from the seafloor is not repeated, the energy represented by this ray remains detectable at long ranges.

where γ_1 is the normal component of the incident wavevector in the water (medium 1), $i\eta_2$ is the normal wavevector component in the elastic seafloor, k is the wavevector magnitude in the water and the ρ values refer to the density of each medium. The function, $P(k)$, is a complicated function of the speed and attenuation of shear waves. Equivalent-fluid models are based upon using an effective density for the seafloor, usually allowed to be complex, to represent the product $P(k)\rho_2$. This generates an approximation to the reflection coefficient without the complication of modeling induced shear components. An equivalent-fluid method introduced by Zhang and Tindle uses the actual solid's compressional sound speed, and a complex density calculated in the limit of low grazing angle and shear speed. For low shear speeds, the behavior of the reflection coefficient bears some resemblance to a non-shear-supporting coefficient; thus, Zhang and Tindle chose to preserve the solid sound speed in order to preserve the "critical angle" effect. However, with substantial shear speeds, the critical angle is no longer the dominant feature of the solid reflection coefficient and equivalent fluids that alter the compressional speed can be more accurate. The equivalent-fluid approximation of Zhang and Tindle can fail when a range of grazing angles is relevant or when the elastic shear speed is not small compared to the sound speed in the water.[1]

A new method has been introduced[4] that searches over effective parameters for the approximate reflection coefficient that minimizes a prescribed cost function over a stated range of grazing angles. In this approach, the bottom sound speed and the complex density's real and imaginary parts are all treated as free parameters in a fit to the elastic reflection coefficient. Currently, the cost function used is the accumulated distance in the complex plane between the approximate and actual reflection coefficient over a discrete set of grazing angle representatives. For a particular experimental geometry, an effective equivalent fluid can be generated by utilizing ray calculations that illustrate the range of grazing angles that are actually relevant to a particular propagation and fitting the reflection coefficient to that of the elastic solid over the angular interval.

2.1. Comparison to benchmark shear model

A preliminary investigation into the performance of the new equivalent-fluid technique involved a comparison to benchmark simulation codes that incorporate a thorough treatment of shear effects in the seafloor solid. These algorithms, however, can be extremely intensive computationally and great care must be taken to avoid numerical instabilities. These limitations meant that a comparison between simulations using an equivalent fluid and corresponding benchmarks could only be executed for limited test cases. The simulation package known as RAMS (Range-dependent Acoustic Modeling with Shear)[5] is used as a benchmark in the comparison. The simulations in this test case are compared on the basis of transmission loss at a single frequency.

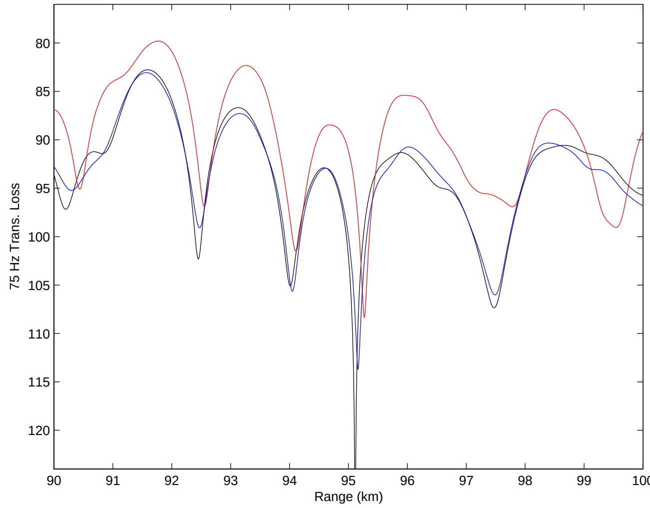

FIGURE 2. Transmission loss at a frequency of 75 Hz is shown as a function of range. The benchmark result (RAMS) is shown in black. The result from a simulation using an equivalent fluid as described by Zhang and Tindle is shown in red. A simulation using an equivalent fluid determined from the new method is depicted in blue.

This test case corresponds to propagation along one of the source-receiver paths in the NPAL experiment.[4] 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). Environmental data from the vicinity of the NPAL source were used. The transmission loss comparison is shown in Figure 2. The new 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. Additional work will involve quantifying these limits on grazing angle and the range of bottom parameters that can be reliably modeled.

2.2. Comparison to data

A data set has become available which provides an excellent opportunity for further validation of equivalent-fluid techniques. During the Basin Acoustic Seamount Scattering EXperiment (BASSEX), the NPAL Kauai source was recorded on a portable receiver at a variety of azimuthal directions and relatively short ranges from a few to a few hundred kilometers. Predictions derived from modeling efforts employing a generalized complex-density equivalent fluid can be compared with the data for a much broader variety of acoustic characteristics (including received level) than was possible with the long-range NPAL results. The results will allow for the isolation of the effect of bottom interaction from the additional effects that complicate signal structure during basin-scale propagation. Any discrepancies between the simulations and the data can be used to refine the numerical algorithms for the calculation of equivalent fluids and constrain the preliminary estimates made for the bottom parameters in the area.

Figure 3 shows the total received level for all frequencies from the broadband source for the data and two simulations using the improved equivalent-fluid method. One equivalent fluid was based on a loose sediment with a sound speed of 1550 m/s and a shear speed of 200 m/s. The other simulation used bottom parameters representing a volcanic basalt (as in Section 2.1). Both simulations reproduce the direct arrival at approximately 2.45 s, with bottom interaction only very near the source, reasonably well. However, an exaggeration of the splitting of this energy in both simulations probably indicates errors in the simulation environment in the immediate vicinity of the source. Further investigation is clearly necessary. The basalt parameters provide somewhat better accuracy in that the two peaks in this arrival have approximately equal level. The clearest distinction between the two sets of bottom parameters can be seen in the received level between approximately 3.1 and 3.3 s. This energy has reflected from the bottom far enough from the source that it represents a truly distinct arrival. This reflected arrival is much more accurately reproduced

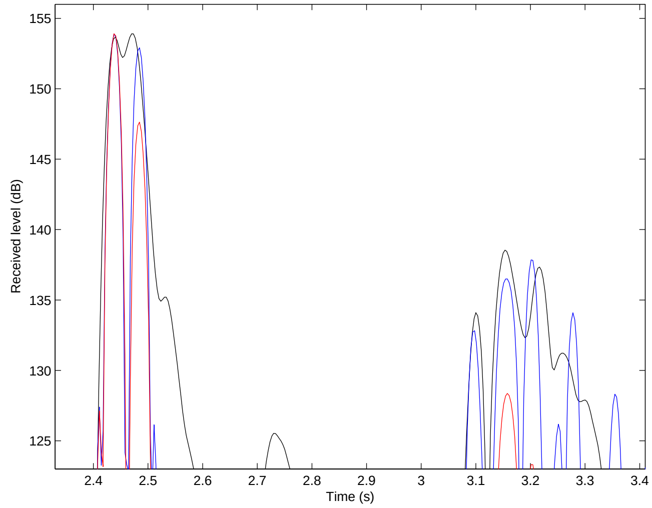

FIGURE 3. Received data from a BASSEX reception at a range of about 3.5 km is shown in black. Results from a simulation using an equivalent fluid corresponding to a soft sediment are shown in red. The simulation using an equivalent fluid intended to estimate a shear-supporting basalt is depicted in blue.

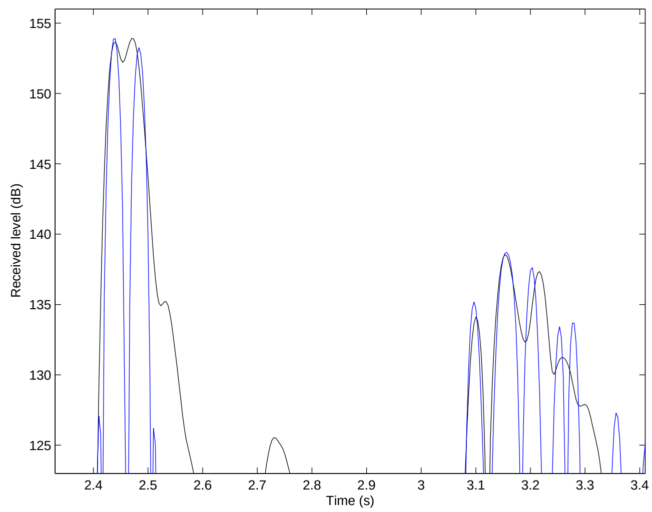

FIGURE 4. The black curve, as in Figure 3, indicates the received level from a 3.5 km BASSEX reception. The blue curve, in this case, is the best match from a series of simulations performed for a set of possible equivalent-fluid parameters.

in the simulation employing basalt parameters. This comparison illustrates the potential for using equivalent-fluid simulations to distinguish the category of seafloor material.

A series of simulations were performed with systematically varied equivalent-fluid parameters. The real and imaginary parts of the complex density were allowed to vary from 0.2 to 2 times the density of the water; the compressional speed varied from 1000 to 3000 m/s. A set of parameters was chosen that offered the best match to the BASSEX data in a preliminary analysis. This match was based on minimizing received level differences in the reflected arrival. A comparison between the BASSEX reception and results from the selected simulation is depicted in Figure 4. Efforts to use this set of equivalent-fluid parameters to characterize the actual elastic solid are underway. This requires a reversal of the process used to construct the equivalent fluid; the elastic solid that corresponds most closely to the equivalent fluid's reflection coefficient must be identified over the domain of grazing angles relevant to the reception.

3. CONCLUSION

Previous work[4] illustrated the benefits of using equivalent fluids to represent the seafloor in simulating travel times for basin-scale propagation. These equivalent fluids are determined by treating the compressional speed, and the real and imaginary parts of the complex density as free parameters in a fit to the reflection coefficient of the actual elastic solid. Preliminary investigations regarding the ability of equivalent-fluid simulations to reproduce additional features of the acoustic field at shorter ranges have been presented. This method for determining the equivalent fluid has been shown to be fairly accurate as compared to benchmark treatments of shear effects and can distinguish amongst general categories of bottom material using received data.

Additional efforts will be directed toward determining the parameters of the elastic seafloor solid using robust and computationally inexpensive equivalent-fluid simulations. First, the correspondence between the environment used in the simulations and BASSEX experimental conditions requires refinement. A determination of actual geoacoustic parameters, given an accurate equivalent fluid, will then involve ray calculations that indicate the grazing angles contributing to the relevant reflected arrival. An estimate of the seafloor parameters can then be based upon correspondence, over the angular interval, between the elastic reflection coefficient and that of the effective equivalent fluid.

ACKNOWLEDGMENTS

This work was supported by a Summer Faculty Research Grant from the University of Southern Mississippi. Acoustic data from BASSEX were provided by Dr. Kevin Heaney. The NPAL Group has made environmental data available, including bathymetry measurements.

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