Integrated Model for the Acoustics of Sediments

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LONG-TERM GOALS

Physically sound models of acoustic interaction with the ocean floor including penetration, reflection and scattering in support of MCM and ASW needs.

OBJECTIVES

The objectives are: (1) Integration of phenomenological components of the Biot plus grain contact physics models, to reconcile the physical constants and processes, with a view to reducing the number of input variables, (2) a comprehensive model for all sediment types and improved modeling of grain contact physics, and (3) the development and testing of sediment acoustic models through a series of at-sea experiments.

APPROACH

The approach may be divided according to the three objective areas:

(1) Fluid, elastic and the Biot-Stoll poro-elastic models are unable to account for the observed frequency dependence of wave speeds, attenuations and reflection loss, found in at-sea experiments since the 1980s, particularly the ONR sponsored experiments SAX99, ASIAEX, SAX04, and SW06 [1-11]. From direct measurements and inversions, it was found that attenuation increases approximately as the second power of the frequency, at frequencies below a few kiloHertz. At higher frequencies, the rate of increase is lower but variable. The Biot-Stoll poro-elastic model goes part of the way toward explaining the measurements but it cannot match the magnitude of the wave speed dispersion and high frequency attenuation trends. Guided by the experimental results, the approach has been to extend the Biot-Stoll model to include the physics of the sand grains, particularly random variations in the grain-grain contact stiffness, squirt flow in the contact region, and the change of pore fluid viscosity as a function of contact width. In this period, the emphasis is on the reducing the number of input variables. This is done through the analysis of mutual dependencies of the model parameters in order to find common factors.

(2) It has been observed that ocean sediments are often inhomogeneous, paticularly in the context of high frequency acoustics. The patchy seabed concept needs to be properly developed and explored in order to assess its impact on acoustic propagation and reverberation models. Practically, all underwater sediments are porous and water-permeable, therefore compatible

with poro-elastic models. Although much effort has been devoted to the modeling of the sandy sediments, there are other sediments, particularly softer sediments, in which the attenuation is proportional to the first power of frequency. The goal of this task is a model that is able to represent a broad range of sediments, and smoothly transition from one type of sediment into another. The approach is to understand the physical processes in a wide range of sediment types and contruct a model that is able to accommodate them. For example, the model must be able to accommodate the frequency dependencies of the attenuation and sound speed in sandy and muddy sediments, and be capable of smoothly transitioning from one to the other, through the adjustment of a few parameters.

(3) The new model(s) are proven by comparison with archived measurements, and new measurements from at-sea experiments. The preferred approach is to isolate the bottom reflected signals and measure bottom loss, and then to use the measured bottom loss as a function of frequency and angle to invert for sediment properties. This approach allows more than one bottom model to be tested, and is less likely to be biased. In this endeavor, archival data from the SAX99, SAX04 and SW06 experiments, and new data from the Noble Mariner 12 Sea trials and the Target and Reverberation Experiment of 2013 (TREXI3) were aggregated for model validation purposes.

WORK COMPLETED

The work completed is as follows:

(1) Progress in the reduction of the number of input parameters has resulted in a model that is comparable in terms of the number of input parameters to existing models, such as the High Frequency Environmental Acoustics (HFEVA) model, yet superior as far as fidelity and the ability to represent real ocean sediments. HFEVA is based on the model found in the APL-UW handbook number 9407 [12]. Progress was achieved through the representation of the frame properties using the contact squirt flow model [13,14], and through the representation of the pore fluid properties using the Revil, Glover, Pezard and Zamora (RGPZ) model developed in the civil engineering community [15], to form an extended Biot model. This model allows the permeability, pore size and tortuosity – parameters that are difficult to measure – to be estimated from the mean grain size, the cementation exponent and a shape coefficient. By these means, an extended Biot model for ocean sediments was constructed that has 8 adjustable input parameters, which is comparable to the elastic HFEVA which has 6 parameters.

(2) The extended Biot model can reproduce the frequency dependence of sound speed and attenuation that is found in the seabed, over a wide range of sediment types, through the inclusion of a distribution of pore sizes following Yamamoto and Turgut [16]. The difference may be illustrated with data from the SW06 experiment which spanned the range of sediment types from sand to silt. The standard deviation of the pore sizes, according to Yamamoto and Turgut, has a strong influence on the frequency dependence of attenuation and sound speed, and it can match the sediment types within this range. This approach provides the theoretical foundation for smoothly transitioning the poro-elastic model between different sediment types, such as sand, silt and mud. It also will be useful in the modeling of sediment inhomogeneity, which may be an important source of acoustic variability in the shallow water environment.

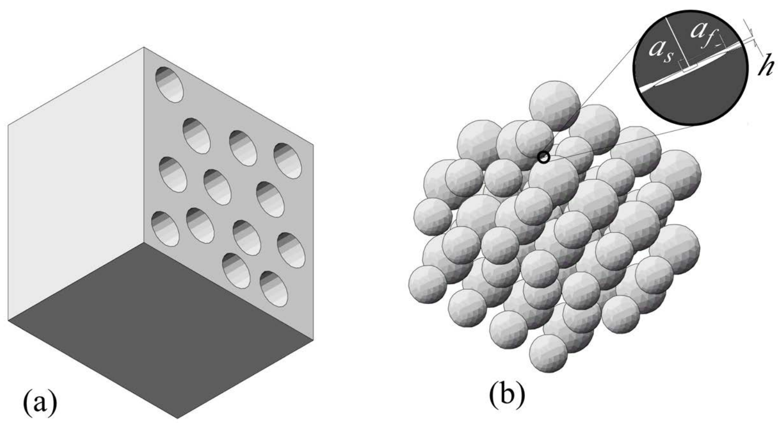
(3) The testing of the models with at-sea measurements, is being realized through a number of collaborative at-sea experiments. Last year, data were collected in a joint experiment under the title Noble Mariner 2012 in cooperation with the NATO Centre for Maritime Research and Experimentation (CMRE). This year participation in the TREX13 experiment was successfully completed, while the data is still being analyzed. Measurements of the bottom roughness using

a laser profiler and normal acoustic reflection loss were made from a remotely operated vehicle (ROV). Variations of around 10 dB in reflection loss signify spatial variations in the acoustic properties of an otherwise uniform seabed.

RESULTS

The results may be summarized as follows:

(1) It has already been shown that fluid and visco-elastic models are unable to reproduce the frequency dependence of wave speeds and attenuations in ocean sediments. A fundamental observation is that ocean sediments are porous structures, that is neither a fluid nor a solid. The Biot-Stoll poro-elastic is a suitable foundation upon which to build a better model, but it is limited by its approximation of the skeletal frame as elastic medium that is punctuated by tubular pores, as illustrated in Fig. 1(a). This is the "swiss cheese" approximation, in which the frame bulk and shear moduli are essentially that of the solid material but diluted by the pores. In glass beads or sand, this model is a poor approximation because the frame stiffness and any associated losses is determined, not so much by the properties if the bulk grain material, but by the stiffness of the grain-grain contact. The contact stiffness may be modeled as a solid contact surrounded by a fluid film, as illustrated in the inset in Fig. 1(b).



(a) (b)

Fig. 1. (a) The skeletal frame in the Biot-Stoll model. (b) The skeletal frame in a granular medium, in which the grain-grain contact is modeled as a solid contact of radius a_s, surrounded by a fluid film of thickness h and radius a_f, as shown in the inset..
[The left panel shows a cube with tubular pores. The right panel shows spherical particles that touch one another. The inset shows a model of the contact region approximated as a solid connection surrounded by a film of fluid.]

The squirt flow associated with the fluid film is an important component of the contact stiffness, and this model tracks the frequency dependence of the wave speeds and attenuations as measured in at-sea experiments quite well. To make the model more user friendly, the difficult to measure terms associated with the pore fluid, including permeability, pore size and tortuosity, are estimated by the Revil, Glover, Pezard and Zamora (RGPZ) model which uses simpler input parameters, including mean grain size and cementation index. Finally, recognizing that the bulk properties of the sediment only vary within a narrow range of values and may be replaced by their average values, an extended Biot model with a reduced number of parameters may be constructed. Using this approach, an extended Biot model equivalent to, but without the limitations of, the sediment types in the HFEVA model was constructed. One version of the parameter values is shown in Table I. Work is still on going to improve the parameterization.

TABLE I. A sample of the extended Biot model equivalent to HFEVA

	Descriptor	M_z ϕ	β	a	m	k_{bo} GPa	k_y GPa	f_k kHz	m_p
4	Sandy Gravel	-1.0	0.16	2.7	1.5	0.20	0.042	5	0.75
5	Very Coarse Sand	-0.5	0.19	2.7	1.5	0.13	0.17	5	0.75
6	Muddy Sandy Gravel	0.0	0.21	2.7	1.5	0.08	0.15	5	0.75
7	Coarse Sand, Gravelly Sand	0.5	0.24	2.7	1.5	0.04	0.13	5	0.50
8	Gravelly Muddy Sand	1.0	0.27	2.7	1.5	0.01	0.41	5	0.25
9	Medium Sand	1.5	0.41	2.7	1.5	0.01	1.81	5	0.00
10	Muddy Gravel	2.0	0.55	2.7	1.5	0.01	1.9	5	0.00
11	Fine Sand, Silty Sand	2.5	0.65	2.7	1.5	0.01	1.62	7	0.00
12	Muddy Sand	3.0	0.74	2.7	1.5	0.01	1.25	8	0.00
13	Very Fine Sand	3.5	0.79	2.7	1.5	0.01	0.095	10	0.00
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16	Sandy Silt Gravelly Mud	5.5	0.88	2.7	1.5	0.01	0.23	10	0.00
17	Medium Silt, Sand-Silt-Clay	6.0	0.90	2.7	1.5	0.01	0.12	10	0.00
18	Sandy Mud	6.5	0.90	2.7	1.5	0.01	0.11	8	0.00
19	Fine Silt, Clayey Silt	7.0	0.90	2.7	1.5	0.01	0.09	6	0.00
20	Sandy Clay	7.5	0.91	2.7	1.5	0.01	0.08	4	0.00
21	Very Fine Silt	8.0	0.91	2.7	1.5	0.01	0.07	2	0.00
22	Silty Clay	8.5	0.91	2.7	1.5	0.01	0.05	2	0.00
23	Clay, All Grades	9.0	0.91	2.7	1.5	0.01	0.03	2	0.00

(2) The Shallow Water Experiment of 2006 (SW06) was conducted over a seabed that had sediment types ranging from coarse sand (0 ϕ) to silt (4 ϕ). With the aid of the pre-experiment survey, acoustic probe measurements at 65 kHz and the inverted sediment properties at several frequencies from 65kHz to as low as 100 Hz [6-9], three representative sets of measurements corresponding to mean grain sizes 1, 2 and 3 ϕ were constructed, as shown in the top row in Fig. 2. The sound speed dispersion of the coarse sand has a more pronounced frequency dependence than the finer sand and the silt. The frequency dependence of attenuation of coarse and fine sand follows one curve, while the silt follows a very different curve. The HFEVA model is compared with the data in the middle row in Fig. 2. It is evident that the constant sound speed and the linear frequency attenuation assumptions that were built in to the model make it impossible to match the data, even if one were to allow the values of grain size to be adjusted up or down. The extended Biot model is shown in the bottom row in Fig. 2, and it has the capacity to match both the frequency dependence of the sound speed and the attenuation of all three sediment types. It provides the foundation for a general model that contains the correct physical processes that is capable of matching a range of different sediment types by simply changing the values of a few parameters.

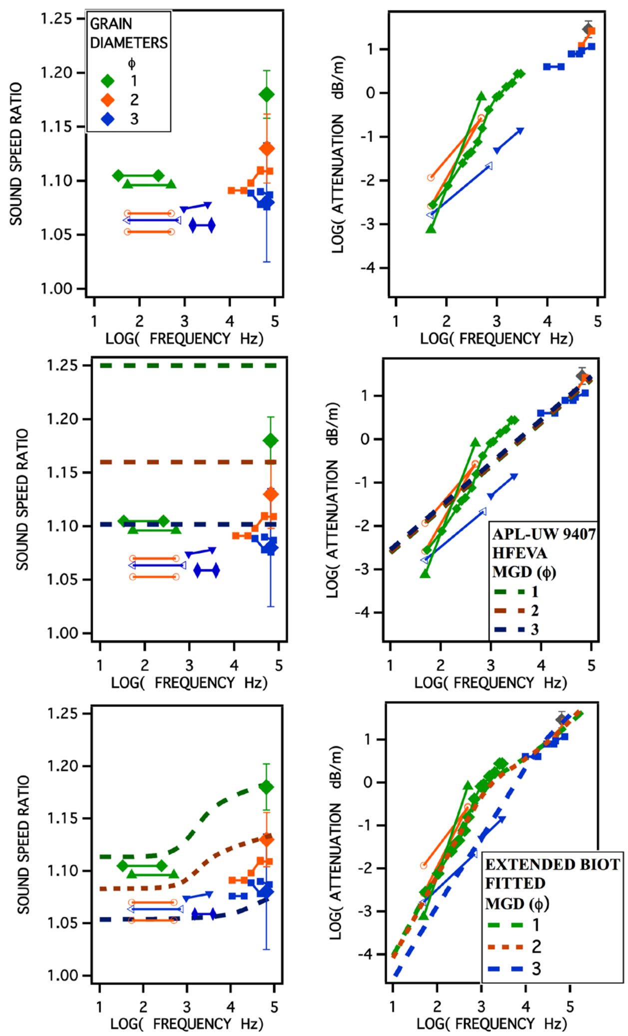

Fig. 2. Measured and inverted sediment sound speeds (top left) and sediment sound attenuation (top right) as a function of frequency at three representative grain sizes 1, 2 and 3 ϕ. Comparison with the HFEVA model (middle row). Comparison with the extended Biot model (bottom row).

[Color coded plots of sediment sound speed and attenuation as a function of frequency at three representative grain sizes. In the top row, only the measured data are shown. In the middle row, they are compared with the HFEVA model. In the bottom row, they are compared with the extended Biot model.]

(3) As part of the TREX13 experiment [17], an instrumented ROV, with laser profiler and acoustic reflection sounder, were deployed at the identified transition sites, as shown in Fig. 3. These are areas that appear to show a change in the texture as perceived by the high-frequency multibeam survey by De Moustier. Video from the high-defnition camera shows a definite difference between the bright sandy areas and the dark strips which appear to be muddy. The acoustically bright sandy regions appear to have a high concentration of shell hash as shown in the example in the left panel of Fig. 4. The darker regions appear to be smooth like mud, as shown in the middle panel of Fig. 4. The transition region was rather chaotic with interlocking patches of sand and mud as shown in right panel of Fig. 4. Analysis of the experimental data is ongoing.

Fig. 3. Map showing the main reverberation measurement track at TREX13, and the detected "transition" zones in which the texture of the sediment appeared to change.
[Map of a part of the TREX13 test area showing the initial multibeam survey swath.]

Fig. 4. High definition video images of the seabed near transition zone 5, showing shell hash in an acoustically bright area (left), a dark area (middle) and a mixed area between the dark and bright areas (left).
[Color images of the seabed corresponding to acoustically bright and dark areas of the reverberation track in TREX13.]

IMPACT/APPLICATIONS

The results will impact Navy underwater acoustic propagation models, particularly where reflection and penetration of sound at the seabed are concerned. It will also impact the future structure of oceanographic databases maintained by Navy offices, including the Naval Oceanographic Office (NAVO). Predictions of sediment wave speeds and attenuations will need to be revised. In addition, the spatial variability of sediment properties will impact the accuracy of sonar performance models.

TRANSITIONS

Work on sediment variability is being transitioned to the active sonar trainers via the High-Fidelity Active Sonar Training (HiFAST) project and to future projects to improve the HFBL database. Some aspects of the ocean sediment model, particularly the frequency dependence of sediment attenuation, have been used in the Ocean Bottom Characterization Initiative (OBCI) project. This work will be used in the new project titled "Seafloor Spatial Variability Mitigation" funded by SPAWAR, for the benefit of NAVO.

RELATED PROJECTS

This project is closely related to most projects under the ONR Underwater Acoustics: High Frequency Sediment Acoustics and Shallow Water Thrusts, especially through the TREX13 experiment (www.trex13.info).

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