Sound Speed and Attenuation in Multiphase Media

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LONG-TERM GOALS

The current research goal is the development of a quantitative understanding and a theoretical treatment of the scattering of sound by non-spherical compressible objects (microbubbles) in multiphase media in the 1-10kHz region.

The second research goal was to explain the observed nonlinear power law frequency-dependent attenuation at lower frequencies (≤ 1 kHz) Biot (1956) [1], Burridge and Keller(1981) [2], and Stoll(1989) [3]predicted that the sandy- sediment frequency-dependent attenuation should be quadratic ; however the observed dependence was less than quadratic. The goal was development of a simplified theory of sediment attenuation verified by measurements that could explain this dependence and be applied to ocean sediments.

OBJECTIVE

The current research objective is the development of a quantitative understanding and a analytical treatment of the scattering of sound by non-spherical compressible objects such as bubbles in sandy/silty and muddy sediments. A second part of this objective is to determine the boundary conditions necessary to describe the sound scattering from microbubble distributions in a multiphase media such as saturated oceanic mud.

The objective of the work has been the determination of frequency dependent attenuation and phase speed characteristics of selected sandy partially saturated sediments at the lower frequencies to verify a simplified our simplified theory that provides a theoretical / experimental basis for the water-sediment boundary condition necessary for the accurate prediction of wide band transmission , scattering and reverberation in shallow waters.

APPROACH

This work was aimed at enhancing our understanding of saturated and partially saturated sandy sediment for frequencies ranging from 100 Hz to 10 kHz. The basic hypothesis is based on a simplified sediment theory [4] and the prediction that high permeability sands will have a quadratic frequency dependent attenuation, and measurements can be described by a relaxation time constant.

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The approach was a combination of theory and experiments to provide a quantitative explanation of the observed nonlinear frequency dependence. [5-7]

A second area of interest is the effect of methane microbubbles in muddy sediments.
The approach here is the use of previous theoretical scattering work on random bubble distributions in water to that of distributions in both saturated sandy and muddy sediments. This approach uses the results from laboratory and field pond experiments.

WORK COMPLETED

Calculations of shallow water transmission loss [TL(f,R) ,TL(f,Δf,R)] and time spread using geo-acoustic profiles agree with experiments over sandy-silty bottom layers when site specific factors [n] are used.

$$\alpha(f) = \alpha(f_o)\cdot(f/f_o)^n \ [dB/m]; \quad 1.6 < n < 2.0.$$

At low frequencies, any disturbance in a Biot medium [1,2] can be represented as a superposition of three basic modal disturbances[4,8,9]. With U(x,t) the local spatial average displacement of the *fluid*, and u(x,t) the local spatial average displacement of the *solid*, one finds three modes of propagation:

1.) The Acoustic mode (locked mode, zero curl) :

$$\nabla^2 U_{ac} - (1/c^2)\partial^2 U_{ac}/\partial t^2 = -(\tau_B/c^2)\partial^3 U_{ac}/\partial t^3; \quad k \approx \omega/c + i(\tau_B/2c)\omega^2 .$$

2.) The Shear mode (locked mode, zero divergence) :

$$\nabla^2 u_{sh} - (\rho/N)\partial^2 u_{sh}/\partial t^2 = -[(\rho_{11}+\rho_{12})^2/Nb]\partial^3 u_{sh}/\partial t^3 .$$

3.) The Darcy mode (non-locked mode, zero curl) :

Every Darcy mode field quantity satisfies this diffusion equation in the first order.

$$\nabla^2 U_d = \kappa \partial U_d/\partial t .$$

For low frequency acoustic disturbances with a hypothetical sediment intermediate distance (L) much greater than the sediment grain size (a) but much less than the acoustic wavelength (λ) , $\{a << L << \lambda\}$, the motion is nearly uniform over distances of order L and displacements of fluid and solid portions nearly the same, a no-slip condition results in

$$\alpha(\omega) = K\cdot\omega^2 \ ; \ K = (\beta a^2 \rho_{eff}/2c_{eff}\eta)\cdot((\rho_s-\rho_f)/\rho_{eff})^2 \chi_s^2 \chi_f$$

Proportionality to frequency-squared at low frequencies is very fundamental, easy to derive from causality considerations The inverse proportionality to viscosity (η)was “sort of implicit” in Biot’s original heuristic theory, but not widely appreciated. the proportionality to square of density difference $(\rho_s-\rho_f)^2$ is fundamental result of the viscous partial retardation mechanism and can by tested by laboratory experiments. The positive dimensionless number β can be estimated by sophisticated computation. [9]

While the theory predicts a power-law dependence with an exponent of $n = 2$, results from experiments conducted under similar conditions yielded an exponent on average of approximately

$$\alpha(f) = \alpha(f_o) \cdot (f / f_o)^n; \ \text{with} \ 0.261 \le \alpha(1\,kHz) \le 0.34 \ .$$

This summary of experimental results [5-7] is consistent with the measurements of Hamilton [10] at 1 kHz.

In our previous report we showed an analytical treatment of a waveguide with a water layer (ρ, c) over a sediment (ρ_b, c_b) with a slow shear wave speed $(c_s < c < c_b)$ shows that the rate of energy conversion to shear waves could explain the apparent additional attenuation, $\alpha_a(f) = \alpha_{swc} + \alpha_i(f)$. Here α_{swc} describes the removal of energy from the water borne field by shear waves. At higher frequencies $(\alpha_a(f) \approx \alpha_i(f))$ while at lower frequencies $(\alpha_a(f) \approx \alpha_{swc})$, thus the observed effective attenuation is determined by a power law relationship between these asymptotes with a less than quadratic dependence. This effective shear wave attenuation can be shown to be proportional to the cube of the shear wave speed, c_s^3 [12]. Hamilton [10] and Stoll [2] report shear wave speeds between 100 to 300 m/s for sandy sediments with porosities of 40-50%. Hastrup [13:121-127] reports empirical relationships that relative speed ratios $1.0 \le c_b / c \le 1.079$ yield shear wave speeds $184 \le c_s \le 400 \ m/s$. While the actual value of the shear wave speed and gradients in the first 5.5 m of sediments are largely unknown, these estimates indicate that the attenuation due to shear wave conversion can vary by a factor of 64. Nevertheless it is possible to quantify the attenuation, $\alpha_a = \alpha_{wc}(f, z) + \alpha_i(f, z)$, and to represent the attenuation as $\alpha_a = \alpha_i(f_o)(f / f_o)^m$ where m is a specific power exponent to compensate for shear in fluid bottom calculations.

Our previous investigations on bubbly liquids and scattering of sound from microbubbles and distributions compared bubbles surrounded by liquids to those in synthetic gels and urethanes. These investigations showed that the presence of a gel or viscoelastic material had the effect of increasing dampening. Experiments conducted in a muddy pond bottom [14] showed the effect of methane microbubbles on the sonic speed and reverberation. A card house theory [15] was adapted to describe mud with considerable water volume fraction. The description of bubble scattering in mud in the 1-10kHz is currently being investigated to describe the effect of methane microbubble distributions on sound speed and attenuation.

RESULTS

Sandy/silty marine sediments are water saturated and consist of diverse tiny rock pebbles. The weight of higher pebbles holds lower pebbles in contact. For low frequency acoustic disturbances, the no-slip condition and viscosity cause the local water displacement near solid surfaces to be nearly the same as that of the neighboring pebbles. Water further from surfaces oscillates relative to solid matter because of mass density difference, and viscosity limits the oscillation amplitude. Derived dissipative wave equation predicts attenuation proportional to frequency squared, proportional to the square of the difference of the densities, and inversely proportional to viscosity [8, 9].

Transmission measurements [5-7] yield intrinsic attenuation estimates for acoustic waves in the underlying sediment, with results that are consistent with attenuation being pro-portional to frequency raised to a power n, with $n \approx 1.8$. Plausible theory [4,8,9] suggests n should be identically 2. The discrepancy can be explained, because the inverse analysis inferences neglected an additional attenuation mechanism where generated lower velocity shear waves carry energy downwards out of the waveguide. This shear effect has a weaker dependence on frequency than the intrinsic attenuation, so the apparent exponent is shifted downward [7].

Experiments were found to have s lower sonic sped than expected and considerable time spread. Methane mircobubbles can affect the sonic speed in muddy sediments. This decrease in sonic speed is consistent with expectations based the Mallock-Wood equation [14,15]. These bubbles can also scatter sound and produce time spread.

IMPACT/APPLICATIONS

The physical justification for the use of a site-specific nonlinear attenuation factors demonstrate validity of fluid-bottom loss models and provide a rational for their use. Furthermore it means that calculations using current geoacoustic representations of sandy-silty bottoms neglecting shear are adequate when nonlinear attenuation is utilized in the mid frequency to low frequency range. These factors can be determined with current research codes that use bottom elasticity.

RELATED PROJECTS

The results of this research have the potential for dramatically improving the use of geo-acoustic models to accurately predict the propagation and dispersion of sound at the low frequencies (~100 Hz) to the high frequencies (~10 kHz). This effort is related to ONR-OA investigations at the WHOI and the RPI and results in sharing resources and students.
This work is related to NAVSEA, NSWC-PC, SERDP under the direction of Drs. K. Commander and R. Lim.

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PUBLICATIONS

Invited Papers (IP), Refereed Proceedings (POMA), Refereed Papers of FY09:

[1] William M. Carey "Transverse coherence lengths, processing limits and implications. (IA) J. Acoust. Soc. Am. 125 2492 (2009)

William M. Carey "Transverse coherence lengths, processing limits and implications" POMA 6 005001 (2009)

[2] William M. Carey, "On the exponential power law for low frequency attenuation in shallow water." (IA) J. Acoust. Soc. Am. 124 2468 (2008)

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[3] Edmund J. Sullivan, William M. Carey, Jason D. Holmes, and James F. Lynch "Passive synthetic aperture as an experimental tool POMA 4 070008 (2009)

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HONORS

The Pioneers of Underwater Acoustics, Silver Medal of the Acoustical Society of America was awarded in June 2007 and was received in November 2007