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CHARACTERISATION OF PROPAGATION PARAMETERS FOR HIGH FREQUENCY SONAR IN TURBID COASTAL WATERS

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Experimental measurements of sound attenuation by suspensions of solid particles have been carried out and the results have been compared with theoretical predictions based on a wave equation formulation for sound propagation in an equivalent homogeneous fluid. Measured values for the viscous absorption of both spherical and non-spherical particles show good agreement with theory as do measurements of the settling rate for glass spheres. The effect of the particles on the sound speed is shown to be negligible.

1. INTRODUCTION

Current sonar performance models are unable to predict with any accuracy the observed temporal and spatial variability in the performance of high frequency sonars in shallow coastal waters. These environments are often characterised by the presence of high concentrations of suspended particles which may be partially responsible for the degradation in sonar performance through their influence on the acoustic propagation parameters. In particular the scattering of sound from the suspended particles and the relative movement of the particles and the ambient fluid can lead to an increase in the volume attenuation coefficient and a sound speed in the suspension which is different from that in the ambient fluid. Both the increased attenuation and the change in the sound speed may be estimated self-consistently by formulating the wave equation for sound propagation in a homogeneous fluid representing the suspension. The results of such an analysis are used to estimate the acoustic propagation parameters for representative suspensions. An experimental technique based on reverberation time measurements has been developed to estimate the absorption coefficient in a suspension, and the results of this method have been compared with the predicted absorption coefficients.

2. THEORY

A suspension may be treated as homogeneous with respect to the acoustic field by considering sufficiently small volume elements that each element may itself be considered homogeneous with respect to the field. For this to be valid the volume elements must be small compared with the wavelength but must also contain many particles. Assuming that these conditions have been met the wave equation for the homogeneous fluid representing the suspension may be written

$$\frac{\partial^2 v}{\partial x^2} = \left(\frac{k_s}{\omega}\right)^2 \frac{\partial^2 v}{\partial t^2}, \tag{1}$$

where k_s is the wavenumber for acoustic waves of angular frequency ω propagating in the suspension. Since the fluid representing the suspension may be considered to be dispersive, the wavenumber may be written

$$k_s = \frac{\omega}{c_s} + i\alpha_{vt}, \tag{2}$$

where c_s is the phase speed in the suspension and $\alpha_{vt} = \alpha_v + \alpha_t$ is the sum of the viscous and thermal absorption coefficients.

It has been shown that the effects of thermal dissipation are not significant for mineral particles suspended in water within the ranges of frequency and particle size of interest. This permits considerable simplification of the expression for the sound speed in suspensions, which may be written [1]

$$c_s^2 = c^2 \left\{ \frac{1 - \varepsilon L \cos\phi}{\left[1 - \varepsilon(1 - \kappa' / \kappa)\right]\left[1 + \varepsilon L(\tau\cos\phi + s\sin\phi)\right]} \right\}, \tag{3}$$

where c is the sound speed in the ambient fluid, κ and κ' are the bulk compressibilities of the fluid and solid components, ε is the volume fraction of suspended particles,

$$\tan\phi = \frac{s}{\sigma + \tau}, \quad L = \frac{\sigma - 1}{\left[(\sigma+\tau)^2 + s^2\right]^{1/2}}, \tag{4}$$

where $\sigma = \rho' / \rho$ is the ratio of solid to fluid densities. These expressions are generally valid for viscous fluid spheres suspended in a viscous fluid, where the viscosity of the spheres is much greater than that of the suspending fluid. In the limiting case of rigid particles, simplifying reductions are possible and we have

$$s = \frac{9}{4\beta a}\left[1 + \frac{1}{\beta a}\right] \quad \text{and} \quad \tau = \frac{1}{2}\left[1 + \frac{9}{2\beta a}\right], \tag{5}$$

where a is the particle radius and $\beta = \sqrt{\omega / 2v}$, where v is the kinematic viscosity of the suspending fluid.

Turning to the attenuation, we may once again neglect the effects of thermal dissipation and write the viscous absorption coefficient as

$$\alpha_v = \left(10\log e^2\right)\frac{\varepsilon\omega(\sigma-1)^2}{2c}\left[\frac{s}{s^2+(\sigma+\tau)^2}\right]. \qquad (6)$$

It may be noted that this expression is in agreement with that derived by Urick [2]. The first term on the right-hand side of Eq. (6) is a constant which converts α_v from Nepers/m to dB/m.

The increase in the volume attenuation coefficient due to sound scattering by the suspended particles begins to become important as ka increases and may be the dominant mechanism for particles which are large compared with the acoustic wavelength ($ka > 1$). This effect was included in a previous paper [3], but for practical sonar applications employing frequencies up to a few hundred kHz (as opposed to ultrasonic instruments operating in the MHz range) the wavelengths are long compared with the sizes of mineral particles likely to remain in suspension. The scattering contribution to the volume attenuation has therefore been omitted from this paper and, indeed, scattering does not contribute to the attenuation coefficient measured in the experimental system described below.

3. EXPERIMENT

The apparatus shown in Figure 1 was used to measure the reverberation times, T_w and T_s, respectively for a volume of particulate-free water and for the same volume with particles suspended in it. The difference between these two values is due to the viscous absorption by the particles, α_v, as defined in Eq. (6), which is obtained from the following expression derived from standard reverberation theory:

$$\alpha_v = \frac{60}{c}\left(\frac{1}{T_s}-\frac{1}{T_w}\right). \qquad (7)$$

The units for the attenuation are dB/m. This can be normalised by dividing by the particle mass concentration giving units of dBm^2/kg.

Because the effect of absorption is small, its effect on the reverberation time of the experimental system must be maximised relative to the other sources of absorption within the system [4]. This has been achieved by using a thin-walled plastic bag which gives a boundary condition close to the ideal of a pressure release surface. Also, the location and immersion of the hydrophones is controlled so that their contribution to the total absorption is constant between tests. Previous tests have shown [5] that because of the variability in the sound field throughout the volume the reverberation time can only be measured to within $\pm 4\%$. This means that suspensions which have very little absorption have a high error because of the similarity in reverberation time between them and the clear-water reference signal. Suspensions with a higher absorption, however, have a more acceptable error. This can be achieved by increasing the concentration or by using particles having greater absorption as the amount of absorption is dependent on the particle radius.

The settling time is measured using a light scattering sensor (LSS). Results from this can be compared to predictions based on the Stokes settling velocity. This gives an indication of the validity of the viscous drag law for interaction between the particles and the fluid which is the basis for the settling theory and the acoustic absorption theory outlined in the previous section. It is particularly useful for investigating non-spherical particles where no simple theory exists.

4. RESULTS

Figure 2 shows the comparison of the theoretical (Stokes Law) and experimental settling rates for glass spheres with a mean diameter of 40 μm. The comparison is quite good in spite of the effect of stirring the suspension in order to put the particles into suspension. This has a more profound effect on finer particles such as the china clay (kaolin) used elsewhere in this study. The suspension was sampled once every second and the data has been smoothed by performing a running average over fifty data points. This removes large fluctuations due to the stirring process and the non-homogeneity of the particle concentration throughout the suspension.

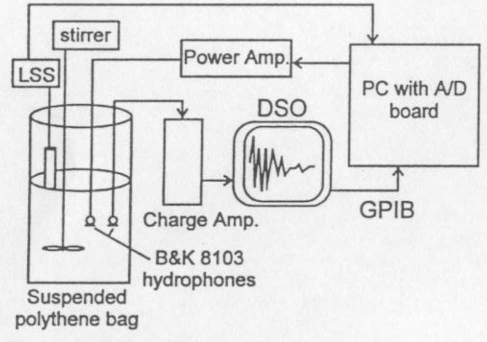

Figure 1 : Schematic diagram of the experimental apparatus.

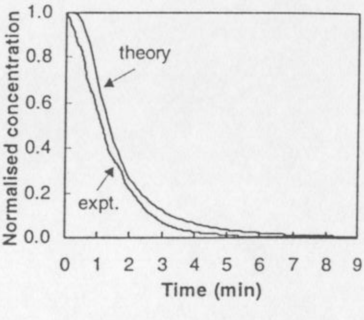

Figure 2 : Theoretical and experimental settling curves for glass spheres.

The results of acoustic tests on a 2.0 kg/m^3 suspension of glass spheres are shown in Figure 3. Agreement with the theory is good and generally within the bounds of the experimental error determined by the accuracy of the reverberation time measurement as outlined earlier. The major fluctuations from theory are an artefact of the particular reference signal which is dependent on the position at which it was taken as discussed in the previous section.

Figure 4 shows three experimental curves for three different concentrations of china clay. They have been normalised and compared to the theory. The three experimental curves are very similar and show good agreement with the theory. Note that the china clay particles are much finer than the glass spheres, with a mean equivalent particle diameter of 0.8 μm. However, the clay particle is plate-like with an aspect ratio of around 30:1 which makes direct comparison with a theory based on the viscous drag on a sphere difficult. It is intended to use the settling measurements to identify a more appropriate drag law. Note also the higher attenuation for the finer particles.

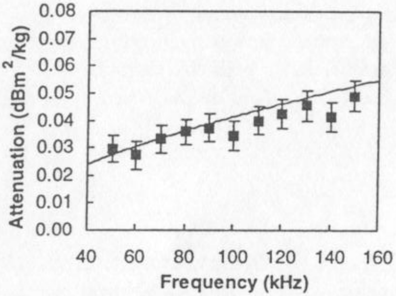

Figure 3 : Normalised attenuation for 2.0 kg/m^3 of glass spheres in water (■) compared to theory (solid line). See text for explanation of error bars.

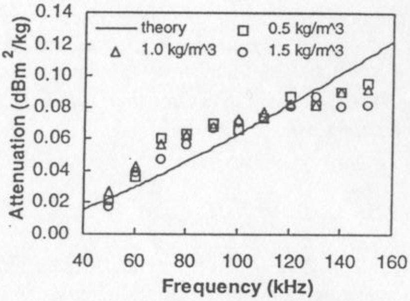

Figure 4 : Theoretical and experimental values of the normalised attenuation for various concentrations of china clay particles in water.

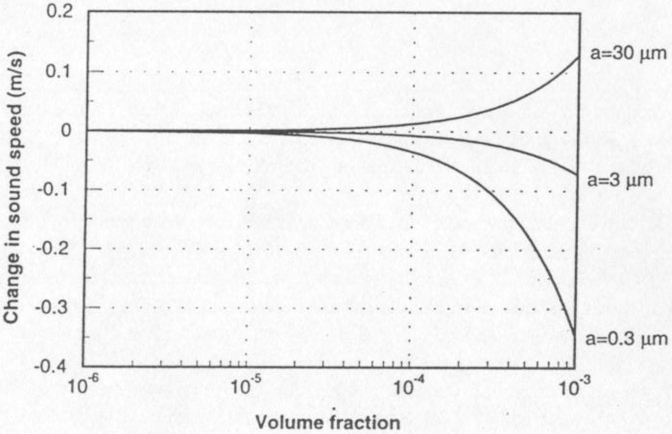

Figure 5 : Difference between speed of sound in a suspension and in clear water as a function of volume fraction of suspended solids for 3 different particle sizes

Figure 5 shows the difference between the sound speed in a suspension and the sound speed in clear water as a function of volume fraction of suspended particles for three different particle sizes. This result was calculated using Eq. (3), with a frequency of 100 kHz, assuming spherical particles with a density of 2400 kg/m^3, such as the glass beads used in some of the some of the experiments. For particles of this density a volume fraction of 10^{-3} is equivalent to a mass concentration of 2.4 kg/m^3, so it may be seen that the change in sound speed resulting from the addition of the particles into the experiment is small for all concentrations considered. Similarly the effect of suspended particles on the sound speed in coastal environments may normally be neglected, except perhaps in the boundary layer near the seabed where particle concentrations may be high enough to significantly influence the sound speed. The fact that increasing the concentration can lead to either an increase or a decrease in the speed of sound, depending on the particle size, results from the competing effects of particle density and compressibility. Ultimately, though, at sufficiently high concentrations the sound speed will always be greater than that in the ambient fluid if the sound speed in the solid is greater than that of the fluid.

5. CONCLUSIONS

Agreement between the theory and experiments is good for both the acoustic tests and the settling of large spherical particles. Reasonable agreement is found for experiment and theory for non-spherical particles despite using a size distribution based on the equivalent spherical diameter for the theory. Work is continuing in order to better quantify the effective particle size of non-spherical particles in terms of their settling rate and their acoustic characteristics, in particular, the tendency of particles to flocculate and how this affects the overall settling rate and acoustic absorption.

REFERENCES

[1] A. Ahuja, "Formulation of wave equation for calculating velocity of sound in suspensions", *J. Acoust. Soc. Am.* **51**, 916 (1972)

[2] R. J. Urick, "The absorption of sound in suspensions of irregular particles", *J. Acoust. Soc. Am.* **20**, 283 (1948)

[3] S. D. Richards, A. D. Heathershaw and P. D. Thorne, "The effect of suspended particulate matter on sound attenuation in seawater", *J. Acoust. Soc. Am.* **100**, 1447 (1996)

[4] N. R. Brown, T. G. Leighton, S. D. Richards and A. D. Heathershaw, "Boundary and volume losses in a diffuse acoustic field near the atmosphere/ocean boundary", *Proceedings of Natural Physical Processes Associated with Sea Surface Sound*, T. G. Leighton Ed., Southampton, U. K., 123, (1997)

[5] N. R. Brown, T. G. Leighton, S. D. Richards and A. D. Heathershaw, "Measurement of viscous sound absorption at 50-150 kHz in a model turbid environment", submitted to *J. Acoust. Soc. Am.*, (1998)