Sound Absorption by Suspended Particulate Matter

N.R. Brown[1], T.G. Leighton[1], S.D. Richards[2] and A.D. Heathershaw[2]

[1]Institute of Sound and Vibration Research
University of Southampton
Southampton, SO17 1BJ, UNITED KINGDOM
Email: nrb@isvr.soton.ac.uk

[2]Defence Evaluation & Research Agency
DERA Winfrith, Winfrith Technology Centre
Dorset, DT2 8XJ, UNITED KINGDOM

Abstract

A series of experiments has been performed to study the viscous absorption of sound by particulate suspensions typical of those found in coastal waters. The effect due to the particles in the frequency range of 50 - 150 kHz has been determined by taking the difference in reverberation times of a volume of water with and without particles. Measured attenuation agrees reasonably well with that predicted by theory for concentrations above 0.5 g/l.

1. Introduction

The acoustic absorption properties of suspended particulate matter in natural bodies of water are not well characterised, though there are a number of applications (e.g., naval mine-hunting sonars, acoustic Doppler current profilers) where such knowledge would be important, particularly in shallow water in the frequency range 50 - 300 kHz. Typical suspensions contain particles in the size range 1 - 100 μm where a variety of shapes and concentrations from 0.1 kgm^{-3} up to 4 kgm^{-3} are possible. They are liable to produce significant absorption losses [1]. There may also be the potential for flocculation and turbulence. The acoustic absorption of such systems is not known and, if models or inversion procedures are to be successfully carried out, must be quantified [2]. Similar comments apply to the inversion processes associated with the acoustic characterisation of suspended particulate matter, where currently untested assumptions must be made regarding the absorptive properties of the suspension [3].

Most of the work concerning suspensions has focused on scattering. Other absorptive processes are, also, better understood. Within the water column, temperature, salinity, pressure, and the concentrations of absorbed gas may vary, affecting the overall acoustic absorption. If bubbles are present, they may contribute significantly to the loss of acoustic energy through thermal and viscous effects, and also through acoustic re-radiation. In addition to being entrained at the water surface through wind, wave, and rain action and carried to around 10 m by Langmuir circulation and turbulence etc., bubbles might also be generated at depth through biological processes, decomposition, or seepage. It is possible to incorporate such factors individually into a description of the acoustic absorption. For deployments in the environment in question, however, not only must the contribution from the suspended particulate matter be quantifiable, but also the possibility of synergy between these factors should be explored. There is, for example, an association between suspended particulate matter and the stabilisation of gas pockets [4].

This paper presents results from an experimental study which aims to quantify the viscous absorption associated with suspended particulate matter. Parallel with this study, theoretical descriptions of the phenomenon are being developed by Richards *et al.* [1, 5], such that theory and experiment can be compared. In this way the viscous absorption effects of the suspensions, once determined, can be incorporated into acoustic propagation models.

2. Experimental Method

2.1 The acoustic tests

A series of investigative tests have been performed in order to evaluate the experimental system and to begin characterising suspensions. The tests performed to date use the reverberation behaviour of a volume of liquid to characterise the attenuation of the fluid. Differences in decay rates may be equated to variations in the absorptive properties of the fluid and the boundaries of the volume. It is important, therefore, that the absorption of the water and container is well known so that the relative contribution due to the addition of particles can be determined. Preliminary tests were performed in a large, thick-walled plastic tank containing approximately 0.6 m^3 of water. Decay traces from this apparatus were compared to traces taken from a smaller system comprising a suspended polythene bag containing 16 ℓ of water. Although the ratio of surface area to volume was increased in the smaller system, the reverberation time increased, emphasising the importance of reducing the losses at the boundaries in order to maximise the relative losses in the fluid.

The system used is shown in schematic form in Figure 1. The signal generation, data acquisition and signal processing are controlled by a personal computer running LabVIEW software. The output signal is sent to a power amplifier and then to a Brüel & Kjær 8103 hydrophone. Signals are received by a second 8103 hydrophone and are monitored by a LeCroy digital storage oscilloscope, after suitable amplification, and are finally transferred for storage and analysis to the computer via a GPIB interface. The 16 ℓ of water is contained in a suspended, thin-walled polythene bag. This provides an approximation to a pressure release surface around the whole volume, thus minimising boundary losses. A mechanical stirrer is used to lift the particulate into suspension and is removed whilst data are being recorded. The dynamic concentration of the solution can be monitored using a light scattering sensor (LSS). This monitors the settling out from suspension of the particulate. The acoustic and LSS measurements are performed separately as the presence of the LSS in the solution has an adverse effect on the reverberation.
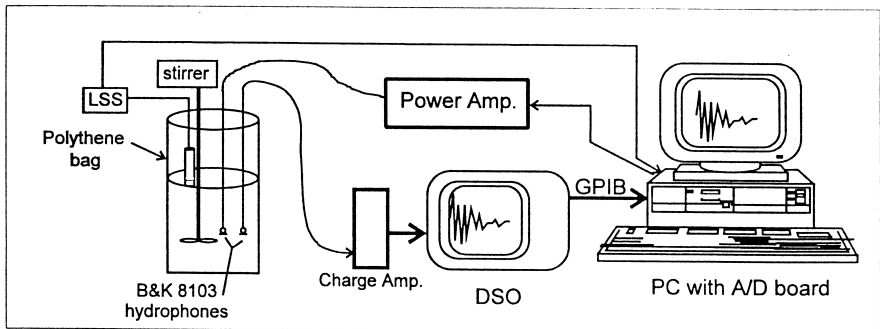

Figure 1: Experimental apparatus.

To measure the reverberation time of the volume it is necessary to record the decay of a sound field as a function of time. Ideally, the reverberation time is determined from the decay of a diffuse sound field. A diffuse sound field is one where the average energy density is the same throughout the volume considered and all directions of propagation are equally probable [6]. The onset of a diffuse sound field in an enclosure can be described by the Schroeder cut-off frequency. This gives an indication of the lowest frequency at which the modal density, i.e., the number of modes per bandwidth, is sufficient to constitute a diffuse field. The Schroeder cut-off frequency, f_{Sch}, can be expressed as [7]

$$f_{Sch} = \left(\frac{c^3}{4\ln 10}\right)^{1/2}\left(\frac{T}{V}\right)^{1/2} \tag{1}$$

where T is the reverberation time of an impulsive noise source (i.e., the time for the sound pressure level to fall by 60 dB), c is the speed of sound in the fluid, and V is the volume of the enclosure. Typical values of f_{Sch} for the system used were between 50 and 75 kHz. This is near the lower limit of the frequency range under consideration in this project. This could be reduced to a value less than 50 kHz by slightly increasing the volume to 20 ℓ, although this is near the strength limit of the bag.

Two techniques have been used so far to generate a sound field: an impulse and a burst of uniform white

noise. Both these techniques produce a broadband sound field. The advantages of a long burst are that the sound field is given time to build up to a constant level before being cut. This improves the signal-to-noise ratio. Also, because there is a more uniform sound field, the decaying sound field is less prone to large perturbations due to direct reflections and particular modes of the volume.

A typical test sequence consists of the solution being stirred until it appears that the particulate is homogeneously spread throughout. The time for this to occur can be verified by the LSS and is of the order of a few seconds. Care must be taken to ensure that particulate does not collect in the eddies generated in the corners of the bag adjacent to the bottom seam during the stirring. Ten noise bursts are sent to the emitting hydrophone and their responses are recorded by the computer. The test sequence takes approximately 35 s. This is about the time limit before significant amounts of particulate have begun to settle out of solution.

The decay rates were determined by applying the method of integrated impulse response (IIR) [8] to the sound field from the time that the driving signal was cut-off. This method was used, even for signals derived from non-impulsional sources, as it gave a smooth estimate of the decay rate. The value of the integrated impulse response represents the ensemble average of the squared noise responses at time t after the onset of decay which is equal to the squared tone-burst response integrated from time t to "infinity." The practical implementation of this method is as follows. The response of the volume to the burst of random noise (which contains the frequency range of interest) is squared then backwards integrated from an upper time limit (some time before the response is exceeded by the background noise) to the lower time limit when the sound burst was cut off. This produces the IIR curves shown in the results section. The slope of this curve is determined from a linear regression over the initial, linear part of the curve. Typically, the lower time limit for the linear regression was 10 ms after the sound was cut off (the burst lasted 20 ms) and the upper limit was variable, the choice depending on the rapidity of the decay.

Post-processing of the results also involved performing the IIR analysis at each of the desired frequency bands. The raw data was filtered after acquisition using a Butterworth bandpass filter in 10 kHz bands over the frequency range of 50 - 150 kHz. Above this frequency, the response becomes increasingly non-linear making it difficult to obtain an estimate for the linear decay of the sound field. The data were also reduced into time bins which represent the RMS of the signal for a used-defined number of samples. This was typically 100 samples. The sampling frequency of the oscilloscope was 500 kHz.

Measurements were made on particulate-free water and then on water containing varying concentrations of glass beads. This type of particle has a high sphericity, as can be seen in Figure 1, and is, thus, representative of the particles used in the theoretical modelling. The difference in reverberation of the two systems determines the contribution of the particles to the total absorption according to the following analysis.
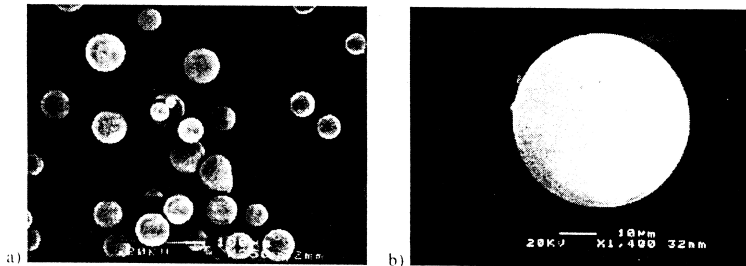

Figure 1: Scanning electron micrographs of the glass beads at a) 250 times magnification and b) 1400 times magnification.

2.2 Determination of absorption from reverberation times

The decay of a diffuse sound field where absorption occurs at the boundary and within the propagating medium is characterised by the reverberation time, T, given by [9]

$$T = \frac{55.3V}{c(A + 8\alpha V)} \qquad (2)$$

where V is the volume (m³), c is the speed of sound of the fluid (m/s), A is the total sound absorption at the boundaries of the volume, and α is the attenuation coefficient of the fluid (Np/m). The quantity $A = S\bar{a}$ is expressed in units of metric sabin, m², where S is the surface area of the volume (m²) and $\bar{a}$ is the average Sabine absorptivity (dimensionless). The first term in the brackets represents the sound absorption at the

boundaries and the second term is the absorption in the medium. If T_w and T_s are the reverberation times of the particulate-free water and the water containing the particulate, respectively, then the difference in the attenuation coefficients of the fluids, $\Delta\alpha$, in dBm^{-1} is given by

$$\Delta\alpha = \left(10\log e^2\right)\frac{55.3}{8c}\left(\frac{1}{T_s} - \frac{1}{T_w}\right).$$ (3)

This represents the attenuation due to the addition of the particulate. This equation makes three important assumptions:

i) that the speed of sound of the solution stays constant as particles are added,

ii) that the volume remains constant, and

iii) that the addition of the particles does not affect the absorptivity of the boundaries.

The sound speed in suspensions can be calculated by using the formulation developed by Ahuja [10]. Assuming a rigid particle (i.e., the particle "viscosity" is much greater than the fluid viscosity), then the change in sound speed for the solutions considered in this work is less than 0.01%. The volume fraction of a 1 g/ℓ solution of glass beads having a density of 2400 kg/m^3 is only 0.042%, so the assumption of constant volume is reasonable. Finally, if changes in acoustic impedance are principally responsible for changes in behaviour at the boundary, then the product of the change in density and change in sound speed represents an error of less than 0.1%. This is reasonable to assume as the bag itself acts like a pressure release surface. Thus, the properties of the bag can be assumed to have almost no contribution to the absorptivity at the boundary. Any change in behaviour at the boundary will be due to changes in the properties of the fluid. This does not take into account the viscous losses due to fluid movement parallel to the bag. If the boundary can be taken to behave as a perfect air-water interface, then the absorption will be due to sound transmission to the surrounding air. For a normally incident plane wave, the absorption coefficient, α_b, is given by the expression [11]

$$\alpha_b = \frac{4\rho_w c_w \rho_a c_a}{\left(\rho_w c_w + \rho_a c_a\right)^2} \approx 0.001$$ (4)

where $\rho_a c_a$ and $\rho_w c_w$ are the specific acoustic impedances of air and water, respectively, and typical values have been taken. The validity of assuming an ideal air-water interface are discussed in section 3.2.

3. Results

3.1 Particle concentration and size distribution measurements

An important aspect of the experimental method is the measurement of the particulate concentration and the particle size distribution. This is because the theory predicts the particulate attenuation is directly proportional to the concentration (for the concentrations under consideration here), a feature which is examined later, and is also a function of the particle size [12]. An infra-red LSS has been used to monitor the concentration of particles in suspension. The particulate is put into solution by means of a mechanical stirrer. Figure 2 shows the variation of concentration with time for a 1.0 g/ℓ solution of glass beads. The time that the stirrer was turned on is obvious from the plot and it is clear that the solution becomes quickly homogenised. The stirrer was stopped at 20 s and the particulate was allowed to settle. The measured concentration shows a gradual, though non-linear, reduction as the particles settle out. The pathlength of the LSS is approximately 0.05 m. It was placed 0.1 m below the surface of a 0.37 m deep volume of water. The large dip in concentration between 65 and 90 s is probably due to large scale circulation of the water producing a particulate-rich eddy, located away from the LSS, which rotates with time. This could make the concentration non-homogeneous throughout the volume even though the average concentration follows the expected exponential decay with time. It should be noted that the initial concentration of 0.1 g/ℓ does not represent a fully settled solution but the suspension concentration before the stirrer was activated.

The particle size distribution was measured following the test by taking a sample of the solution and analysing it in a laser diffraction analyser. This determines the volume distribution of particles over the size range, 0.4 µm - 1000 µm. This means. however, that the dynamic variation of the particle size distribution cannot readily be obtained as a relatively substantial volume of water must be taken from the solution. This would obviously affect the reverberation characteristics of the volume. Figure 3 shows the particle size distribution for the glass beads used in this study.
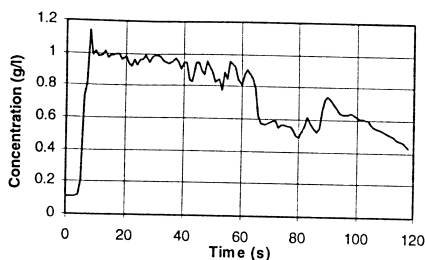
Figure 2: Variation of suspended particulate concentration with time of a 1.0 g/ℓ solution.

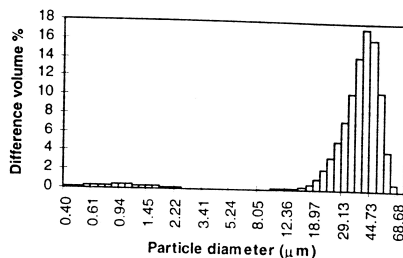Figure 3: Particle size distribution for glass beads.

3.2 Glass bead solutions

A series of tests were performed on glass bead solutions with concentrations from 0.0 - 1.0 g/ℓ. The water used was passed through a reverse osmosis system and then filtered to remove any remaining particulate matter. As can be seen from Figure 3, there are very low concentrations of particles in the micron range. The glass beads were added in 3.2 g steps, i.e., 0.2 g/ℓ increments. The water was degassed prior to testing. The dissolved oxygen content varied from 41 - 60 % over the course of the measurements.

Figure 4 shows typical binned time traces and their corresponding IIR curve at 100 kHz for pure water and a 1.0 g/ℓ solution of glass beads. The IIR curve clearly represents the decay rate of the sound energy in the volume. The y-axis scale is the sound pressure level (SPL) in dB re 1 μPa. This only relates to the measured time trace. The reverberation times calculated for these traces were 0.233 s for the pure water and 0.132 s for the glass bead solution. At this frequency there is almost a 60 dB dynamic range. The output burst lasted 20 ms and the increase in the sound pressure over this time is clearly seen in the figures. The effect of the particulate is clearly seen.
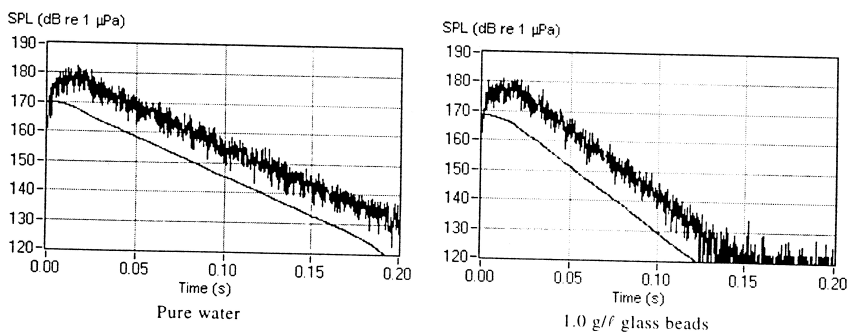

Pure water

1.0 g/ℓ glass beads

Figure 4: Typical binned time traces at 100 kHz for reverberation time calculation (upper trace) with their corresponding integrated impulse response curve (lower trace).

Figures 5 and 6 show, respectively, the reverberation time and the attenuation due to the addition of particles, $\Delta\alpha$, as functions of frequency. It should be noted that the reverberation times have been corrected for temperature and atmospheric pressure [13], which both affect the speed of sound of water. Because the temperature of the water changed over the course of the experiment from 16.0 - 15.1 °C, the reverberation times have been normalised to the conditions present for the particulate-free water measurements, i.e., 16.0 °C. Figure 5 shows that the reverberation time for the pure water decreases with increasing frequency, as is expected as the attenuation increases with increasing frequency. As particles are added, the reverberation time similarly decreases and, in general, as more particulate is added the reverberation time decreases. This leads to a general increase in attenuation with increasing frequency, as expected. If the attenuation is normalised with respect to concentration, Figure 7, then it is clear that the curves do not reduce to a single value. The reasons for this are not yet clear. The variations at low frequencies for the more dilute solutions may be because the measurements

are made close to, or below, the Schroeder frequency. As the concentration increases and, thus, the reverberation time reduces, the Schroeder frequency reduces to around 50 kHz. The more dilute solutions show the greatest variation from the expected values. Considering the small variations in attenuation for these solutions, this is not altogether unexpected. The bold line in Figure 7 is the predicted normalised attenuation for a glass bead solution of the given particle size distribution. The measured attenuation agrees reasonably well with the prediction, particularly for the higher concentration solutions. The reasons for the discrepancies, especially for low concentrations, are discussed below.
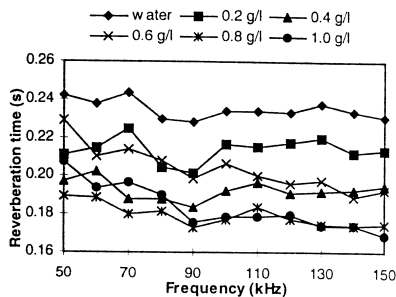

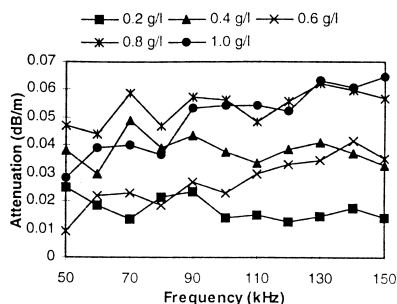Figure 5: Reverberation time for various concentrations of glass beads.

Figure 6: Particulate attenuation for various concentrations of glass beads.
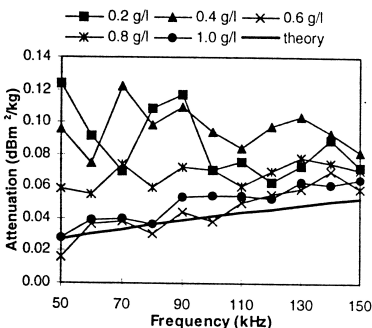

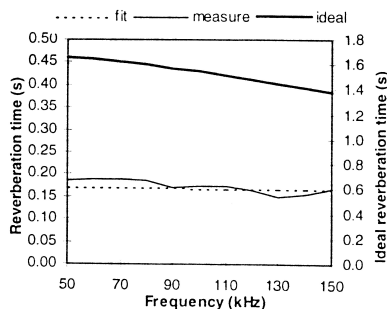Figure 7: Normalised particulate attenuation for various concentrations.

Figure 8: Reverberation times for distilled water. N.B. Ideal curve relates to right hand scale.

Consider the predicted reverberation time for particulate-free water calculated using an empirical formula for the attenuation of distilled water [14]. If it is assumed for the moment that all the boundaries behave as a perfect air-water interface for normally-incident rays, then it is evident that the measured reverberation time (and, hence, the attenuation) for pure water is considerably less than predicted (Figure 8). This is not unexpected; in a diffuse sound field many wall reflections will be at oblique incidence. In order to achieve a good fit to the measured data, the absorptivity at the boundary, i.e., the acoustic intensity transmission coefficient, must be increased from 0.001, for an ideal air-water interface at normal incidence, to 0.015 for the air-water interface and 0.0093 for the bag-water interface. These values were determined by taking reverberation measurements with different volumes of water and, thus, different proportions of surface area of the bag and the free surface. The absorption coefficients of the two types of boundary were varied in order to minimise the variation of the total absorption over the different water volumes and the frequency range of interest. Using these values of absorption and assuming ideal water, the fit to the measured reverberation is quite good. The calculation of the attenuation due to the addition of the particles is unaffected by the exact values of the boundary losses (provided they are small) because, first, this is not a function of the boundary properties, as shown in (3); and, second, because the difference in reverberation time is used, the attenuation of the water is eliminated. If, however, the absolute attenuation of the pure water or the water containing particles is to be found, a better understanding of

the losses at the boundaries must be obtained. This should also improve the measurement of dilute solutions where the variation from pure water attenuation is slight.

As mentioned previously, each result represents the average of ten measurements taken over 35 s. Figure 10 shows the reverberation times for particulate-free water and two concentrations with error bars equal to one standard deviation of the ten measurements at each of the frequency steps. Although there is some overlap, particularly at low frequencies, the amount of variation suggests that the observed trend is fairly consistent. If the variation of reverberation time with time is plotted for one solution (1.0 g/ℓ in this case) at a number of frequencies (Figure 11), then it is clear that there is a general increase in reverberation time as the test progresses. This is consistent with some of the particulate settling out of the solution and reducing the attenuation. There may also be a contribution from the variation in fluid movement as the solution calms after the stirring.
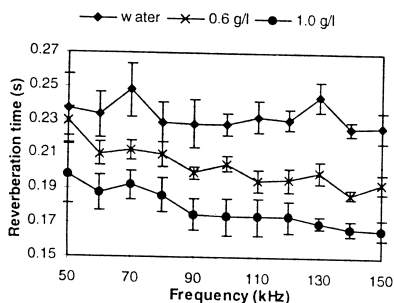

Figure 10: Reverberation times for water and selected solutions with 1 standard deviation error bars.
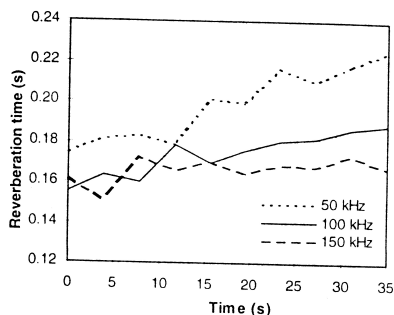
Figure 11: Variation of reverberation time with time for a 1.0 g/ℓ solution at three frequencies.

4. Conclusion

A series of reverberation tests performed on particulate-free water and water containing various concentrations of spherical glass beads have shown that the attenuation due to the particles is a readily measurable parameter using this technique. The attenuation measured agrees well with that predicted by theory for solutions with a concentration greater than 0.5 g/ℓ. Testing is continuing in order to obtain a better understanding of the loss mechanisms in the experimental system. In particular, the losses at the boundaries are being investigated. This may also resolve the variation from the predicted attenuation for the more dilute solutions. One aspect requiring investigation is the effect dissolved oxygen has on the measurements. As mentioned in section 3.2, in the tests performed to date the dissolved oxygen level showed a gradual increase over time. The contribution this makes to the reverberation behaviour requires further investigation. The dynamic concentration has been measured and this shows a gradual reduction with time which may, in part, explain the variation of reverberation time over the course of the test. The particle size distribution may also vary with time but, as yet, there is no method for monitoring this. It is evident that the contribution to attenuation of suspended particles due to viscous attenuation is small but, nevertheless, significant and should be taken into account in propagation models for turbid waters.

5. Acknowledgements

6. References

[1] S.D. Richards, A.D. Heathershaw and P.D. Thorne, "The effect of suspended particulate matter on sound attenuation in seawater," *Journal of the Acoustical Society of America*, vol. 100(3), pp.1447-50, 1996.

[2] A.D. Heathershaw and P.D. Thorne, "Impact of suspended particulate matter on acoustic propagation in turbid coastal waters," in *Proceedings of the. International Maritime Defence Exhibition and Conference*, vol. 2, Greenwich, London, pp.111-21, March 1995.

[3] S. Sun, P. Thorne, I. Bjørnø and T. Mazoyer, "Observations of acoustic backscatter by elastic cubes," in *Proceedings of the Third European Conference on Underwater Acoustics*, Heraklion, Crete, pp.51-6, June 1996.

[4] T.G. Leighton, The Acoustic Bubble, Academic Press, London, pp.78-83, 1994.

[5] S.D. Richards, A.D. Heathershaw, N.R. Brown and T.G. Leighton, "The effect of suspended particulate matter on the performance of high frequency sonars in turbid coastal waters," in these proceedings.

[6] L.E Kinsler, A.R. Frey, A.B. Coppens and J.V. Sanders, Fundamentals of Acoustics, 3rd ed., John Wiley & Sons, New York, p.313, 1982.

[7] A.D. Pierce, Acoustics: an introduction to its physical principles and applications, McGraw Hill, New York, p. 294, 1981.

[8] M.R. Schroeder, "New method of measuring reverberation time," *Journal of the Acoustical Society of America*, vol. 37(3), pp. 409-12, 1965.

[9] L.E. Kinsler *et al.*, *op. cit.*, p.319.

[10]A.S. Ahuja, "Formulation of wave equation for calculating velocity of sound in suspensions," *Journal of the Acoustical Society of America*, vol. 51(3), pp. 916-19, 1972.

[11]L.E. Kinsler *et al.*, *op. cit.*, p.126.

[12]R.J. Urick, "The absorption of sound in suspensions of irregular particles," *Journal of the Acoustical Society of America*, vol. 20(3), pp. 283-9, 1948.

[13]L.E. Kinsler *et al.*, *op. cit.*, p.107.

[14]F.H. Fisher and V.P. Simmons, "Sound absorption in sea water," *Journal of the Acoustical Society of America*, vol. 62(3), pp.558-64, 1977.