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Effect of Acoustic Absorption by Hydrophone and Cable on a Reverberation Technique for Measuring Sound Absorption Coefficient of Particulate Suspensions

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INSTITUTE OF SOUND AND VIBRATION RESEARCH

FLUID DYNAMICS AND ACOUSTICS GROUP

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by

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Abstract

A technique has been developed to measure the sound absorption coefficient of particulate suspensions using a reverberation time technique. This technique measures the change in the reverberation time of the test volume of water when small particles are added. It is described in detail in other publications, which are referenced. When measuring a reverberant sound field, it is good practice to make measurements at a number of discreet locations, and spatially average the results. This of course relies upon the assumption that the making of the measurement does not significantly affect the parameter which is being measured. However in the experiment described here, this is not the case. When the hydrophone position is changed (in order to measure the sound field at several locations), the resulting changes in the length of cable that is submerged cause changes in the absorption similar to those which result from the addition of particles. In this report, this effect is illustrated. Critically, this is not simply a phenomenon which is interesting its own right; rather, its influence is so great that it prevents the taking of measurements throughout the water volume. Instead a scheme is presented whereby the uncertainty, which comes from being able to take measurements in one location only, is estimated by taking measurements over a horizontal plane (a process which keeps constant the length of cable which is submerged). The error in the calculation of the particulate attenuation is principally due to the error in the measurement of the reverberation time given the constraint of taking the measurements at a single location rather than making a spatial average. It is noted that, since the absorption is obtained from the difference in reverberation time of particulate-free water and a given particulate suspension, then the more dilute suspensions (where the difference is slight) are more affected by the error in determining the reverberation time.

1. Introduction

This report details a facet of a larger programme aimed at measuring the attenuation of a particulate suspension due to viscous absorption. This absorption is caused by the relative movement of the particles and the fluid when they are subjected to an acoustic field. The rationale for performing the tests using a reverberation technique, the use of a test volume where the fluid is contained by a thin plastic membrane, and the experimental protocol, are described elsewhere [1-3].

The current report outlines avenues of interest that have been followed during the development of the experimental protocol. The first of these is the effect of stirring the suspension as it relates to turbulence and air entrainment. To maintain the particles in suspension the water must be stirred. The resulting fluid flow and turbulence alter the observed reverberation time. To examine the phenomenon, the use of magnetic particles which can be suspended without stirring was proposed. A preliminary investigation into magnetic particles has been performed and a number of issues have been raised about their potential use. Care would need to be taken to generate a sufficiently strong magnetic field to support the particles, but measures would also have to be found to stop the particles from coalescing under the influence of the magnetic field. Tests on magnetic particles did not progress belonged this preliminary stage., because the main interest in studying magnetic particles for this project would be to obtain the ability to study heavy particles without having to introduce turbulence to maintain them in suspension. However, concurrent with these tests, analysis has indicated that the attenuation due to turbulence is several orders of magnitude less than that which has been observed [2, 4].

The second (and larger) arose as a result of attempts to obtain spatially-averaged measurements of the sound field. Tests performed to estimate the degree to which the sound field in the water volume was diffuse highlighted the effect of hydrophone absorption. In light of this, further tests were performed to estimate the spatial average of the sound field over a plane, and these tests showed that there was some spatial variation. This led to an estimate of the error for the reverberation time due to the restriction of measuring the sound field at a single point rather than making a spatial average. This error has been used as the basis for estimating the confidence in the measurements for absorption due to the particles. The results leading to this are presented in Section 3.

Following this assessment it was decided to perform another series of tests using glass beads with an improved experimental technique and over an increased range of particle concentrations. The results from these tests were more consistent than the earlier tests and these results formed the basis of a paper [2] which gives good agreement between the experiment and theory when both are applied to spherical particles. Experiments with non-spherical particles and a corresponding theoretical approach are currently being prepared for publication. Other papers examine the implications of the acoustic absorption of suspended particulate material for sonar detection in turbid environments [5, 6] and for developing acoustic sensors for sediment transport by rivers [7].

2. Method

2.1 Protocol

The results presented in this report were made using the experimental rig described previously [2, 3]. Following on from the presentation of the preliminary test results [3], and prior to the presentation of the results in reference [2], an error analysis was performed to provide an estimate of the reliability of the test method. The results from this analysis showed that the ping to ping variation did not account for the observed variation in the attenuation at various concentrations. It was thought that there may be a significant spatial variation in the volume. This was subsequently investigated by making reverberation measurements throughout the volume for particulate-free water.

Examination of the results for the spatial averaging showed that the immersion of the hydrophones into the water significantly altered the reverberation time implying an increase in absorption due to the hydrophone. This effect was further examined by measuring the reverberation time for water with the hydrophones fixed but an additional length of hydrophone cable inserted into the water. From this it was clear that the only spatial average that could be simply obtained would be in a plane where the amount of hydrophone cable in the water was constant. A spatial average in a plane was performed and the results showed a reverberation time variation of 4% based on the standard deviation from the eight measurement locations. This formed the basis of the error estimate for the measurement of reverberation time when made at a single location.

2.2 The acoustic tests

The acoustic test still relies on taking the difference in reverberation behaviour between a "clear water" measurement and a particulate suspension. This eliminates the need to know the exact attenuation of the water and the absorption losses at the boundaries and that due to the hydrophones. The decay rate of the reverberant sound field is determined by applying the method of integrated impulse response (IIR) [3, 8] to the sound field from the time that the driving signal is cut-off. This method is used, even for signals derived from non-impulsive sources, as it gives a smooth estimate of the decay rate. This technique was outlined in the previous report.

The important change in the test protocol has been the rigorous placement of the hydrophones so that the amount of hydrophone in the water and their position in the bag does not vary over the test period. This permits the use of the error estimate made by taking the spatial average in a plane.

The application of a Kramers-Kronig technique to obtain the attenuation from the complex sound speed was deemed to be unsuitable for the level of dispersion likely with the particulates studied here [4].

3 Results

3.1 Spatial variation

To test the assumption of a diffuse sound field, a test was performed to measure the spatial average of the reverberant sound field. The test consisted of taking ten pings at each of twelve receiver positions and repeating this for three different source positions. The twelve receiver positions were, approximately, at three different depths in the bag, i.e., four positions at each depth, which corresponded to the depths of the three source positions. Figure 1 shows the reverberation times for these tests averaged in two different ways: first (Fig. 1(a)-(c)), averaging all the pings for the receiver located at one of the three depths with the source at the three different depths; then the converse of this (Fig. 1(d)-(f)) where the pings are averaged for the source at one of the three depths and the receiver at each of the three depths. The source positions are designated s1, s2, and s3 and the receiver positions r1, r2, and r3, which represent the average of the four receiver positions at each depth. In both cases 1 is the shallowest position and 3 is the deepest. As would be expected, there is considerable similarity between the two analyses, the differences being due to the slight variations in the amount of hydrophone submerged as the hydrophone was repositioned at nominally the same location. The significant variation, however, is that due to the amount of hydrophone submerged in the water. Clearly, when the source or receiver is deepest (Fig. 1(c) and (f), respectively) the reverberation time is shortest indicating the maximum absorption which is due directly to the presence of the hydrophones. Each of the figures shows that when one of the transducers is fixed, the amount of absorption increases (reverberation time decreases) as the second hydrophone is lowered into the bag. The error bars in the figures represent one standard deviation from the mean of the forty pings at each source-receiver position pair when the receiver was at the four positions at the same depth. Though it is somewhat difficult to see from Fig. 1, the variations between the curves are only within the bounds of the error bars when there is the maximum amount of absorption (Fig. 1(c) and (f)).

3.2 Absorption by the hydrophones

Having shown that the amount of hydrophone in the water had a significant effect on the total absorption of the system, a test was performed to try to quantify the absorption of the additional hydrophone cable. Figure 2 shows the effect of inserting various lengths of hydrophone cable into the water whilst keeping the source and receiver hydrophones fixed. The cable was inserted in 10 cm increments and the measured reverberation times are compared in Figure 2 to the baseline value when no additional hydrophone cable was present. The error bars (though they are mostly obscured by the data point symbol) represent the standard deviation of the thirty pings taken for each of the lengths of cable inserted. The actual attenuation level has not been calculated but every 10 cm of cable represents a similar absorption to a 1.0 kg/m^3 suspension of the glass beads tested in this study. If an absolute estimation of the hydrophone absorption was required (for example for subsequent subtraction, along with the boundary losses, from the overall absorption, to give an absolute estimate for the absorption due to the water or the suspension), this could readily be obtained by measuring the additional absorption due to a third hydrophone, rather than just a length of hydrophone cable.

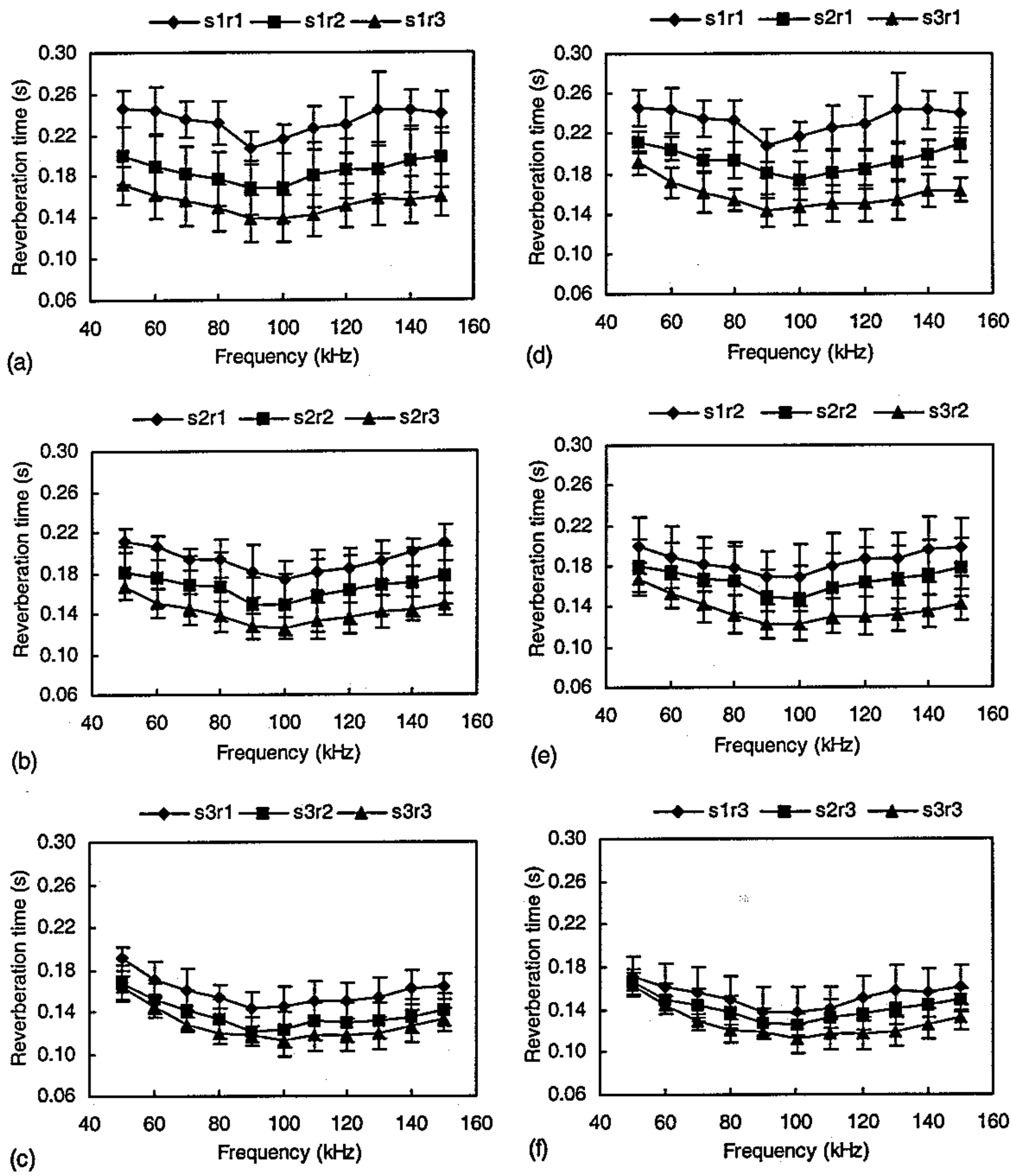

Figure 1. Reverberation time for water with source (s) and receiver (r) at three different depths. Each receiver depth averages four different positions at that depth. (a) - (c) each have the source at one depth and the receiver at three depths; (d) - (f) have the receiver at one depth and the source at three depths. The numbers 1-3 represent the three depths, 1 being the shallowest and 3 the deepest.

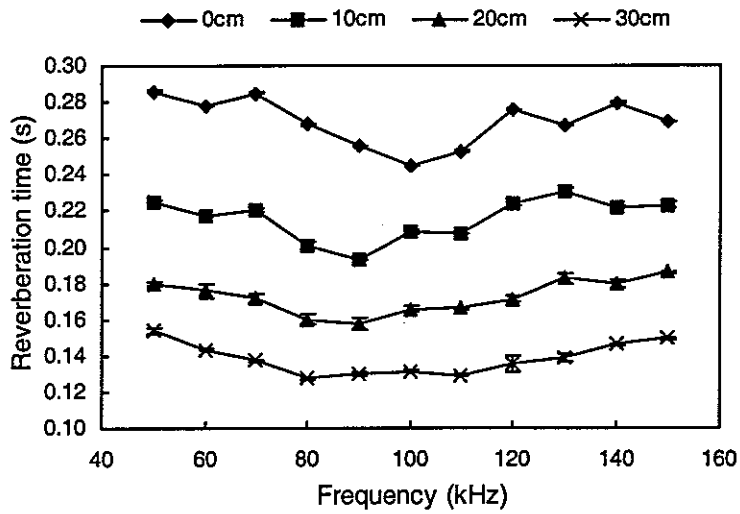

Figure 2. Reverberation time for water with the indicated lengths of hydrophone cable inserted. Error bars are mainly obscured by the data point marks but represent the standard deviation of 30 pings for each length of cable.

3.3 Error analysis

The parameter of interest in this study is the absorption due to the particulate added to a volume of water. This absorption, denoted $\Delta\alpha$, is obtained from the expression

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

where c is the speed of sound of the water (which has been shown to be essentially the same as for the suspension [3]), and T_w and T_s are the reverberation times of the particulate-free water and the water containing the particulate, respectively. When the data are processed, the particulate absorption is normalised with respect to the particulate concentration. This introduces a further error based on the estimate of the concentration, which involves the error in measuring the volume and the cumulative error of adding particulate in a series of increments.

The reverberation time is obtained by measuring the slope of the decaying sound field in the form of the IIR. The IIR is generally very linear so the fit of the linear regression gives a very reliable estimate of the reverberation time. For calm water cases, the ping to ping variation may give variations in the reverberation time of less than 1%. If an error of this magnitude is used to estimate the error in the particulate absorption then the overall error is still less than 1%. This does not account for the observed variation from the prediction or between suspensions of different concentrations.

From the observations of the absorption due to the hydrophones made while trying to estimate the spatial variation of the sound field, it was thought that the spatial variation may play a significant part in the correct estimation of the reverberation time. To check on this variation an experiment was performed whereby the spatial variation in a single plane was measured. This meant that the amount of hydrophone cable in the water was constant. The source was fixed and the receiver was moved in a straight line across the bag approximately 25 mm from the vertical axis of the bag. Figure 3 shows the reverberation times for each of the eight positions measured across the bag. Twenty pings were made at each position. The bold line represents the mean of all the pings and the error bars are ± 1 standard deviation from the mean. This is equivalent to a 4% error in the estimate of the reverberation time. The results also show that this variation is approximately equal over all frequencies. The upshot of this is that if the reverberation time is measured in one position, then it, at best, represents the true reverberation time to within 4%. This value has been used in the calculation of the errors for the particulate absorption [2]. The errors in the overall calculation of the particulate absorption are shown in Table 1 for concentrations above 0.5 kg/m^3. The 0.25 kg/m^3 suspension is ignored because of the overlap between the reference signal and the suspension signal which produced some negative attenuation. The improvement in the error as the concentration increases is readily apparent.

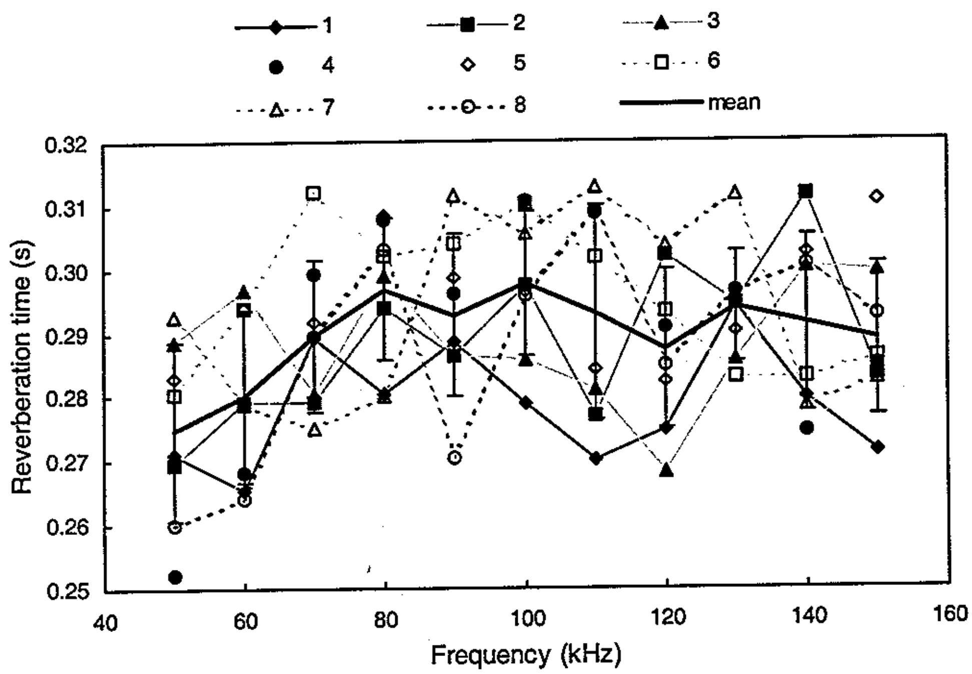

Figure 3. Reverberation time for water measured in a plane. The bold line is the mean of all the pings and the error bars represent ± 1 standard deviation which is equivalent to a 4% error in the estimate of the reverberation time. Position 1 is the hydrophone placed near one wall moving across the bag to position 8 near the opposite wall.

Table 1. Error in the calculation of the normalised particulate absorption.

Concentration (kg m^{-3})	Error in normalised absorption (%)
0.50	45
0.75	24
1.00	23
1.25	19
1.50	17
1.75	15
2.00	14

3.4 Absorption by particles

The results from the absorption tests on glass bead suspensions are fully described in reference [2]. The most important result is shown in Fig. 6 of that article. It shows the comparison between the predicted and the measured attenuation for eight concentrations of particulate. The attenuation has been normalised by dividing the attenuation in dB/m by the concentration in kg m^{-3}. Because the attenuation is a linear function with concentration for the suspensions under consideration, all the curves should reduce to a single line. It is clear that the more dilute suspensions show the greatest variation from the prediction. This is to be expected, as they produce the least variation from the clear-water attenuation and so the difference between the two is smallest and, hence, most prone to experimental error. The agreement at the higher concentrations is reasonable and is comparable to the accuracy available using other methods [9].

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