Natural Physical Processes associated with Sea Surface Sound

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Boundary and volume losses in a diffuse acoustic field near the atmosphere/ocean boundary

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Abstract
As part of a study into the viscous absorption of sound by particulate solutions, a number of interesting phenomena have been observed which are related to the losses at an air-water boundary. A reverberation system using a thin membrane containing water has shown that, whilst relative measurements of absorption mechanisms can be obtained, the absolute measurement of attenuation in a solution is limited by superfluous factors. Possible reasons include: loss at the surface by transmission, absorption in the acoustic boundary layer, bubbles and dissolved gas, particles, and turbulence. This paper presents a discussion of these mechanisms in an effort to show their relative importance to the overall losses from the system under study.

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 at low ultrasonic frequencies. 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. Most of the work on suspensions has concentrated on scattering, though they can produce significant acoustic absorption [1]. Other absorptive processes are 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 [2].

In order to investigate the attenuation of suspended particulate matter, a reverberation technique has been used whereby the difference in decay rates for particulate-free water and water containing particulate gives the attenuation due to the particulate itself. Because the difference between the two is used, neither the attenuation at the boundaries nor other constant sources of loss affects the outcome. All other losses are cancelled out, leaving an absolute measure of the particulate absorption. If, however, an absolute measurement of the attenuation of the solution as a whole were required, the contribution from the boundaries and from other dissipative phenomena would need to be quantified either experimentally or analytically. A number of measurements have been performed to gauge the magnitude of the effect of these non-particulate mechanisms. Their contribution to the total absorption of the system is far from negligible. The principal areas of investigation presented here are the boundary losses at both a water-air interface and a water-bag-air interface, the acoustic boundary layer, turbulence, the effect of the hydrophone mounts, and the rôle of bubbles and dissolved oxygen in the overall attenuation. Most of these phenomena are also found in the acoustics of the atmosphere/ocean boundary.

2. Experimental system

The basic system is shown in Fig. 1. It consists of a thin-walled polythene bag (0.03 mm thick) supported on a ring which is itself suspended from three fine wires. The bag can support up to 0.02 m^3 of water. The signal generation, data acquisition and signal processing are controlled by a personal computer. The output signal is sent to a power amplifier and then to a hydrophone. Signals are received by a second hydrophone and are monitored, after suitable amplification, by a digital storage oscilloscope. Finally they are transferred for storage and analysis to the computer via a GPIB interface. 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. The water was degassed in a vacuum chamber prior to use and the level of dissolved oxygen was monitored throughout the test as an indirect check on the level of bubbles and, in particular, on the effect the stirring had on regassing the solution.

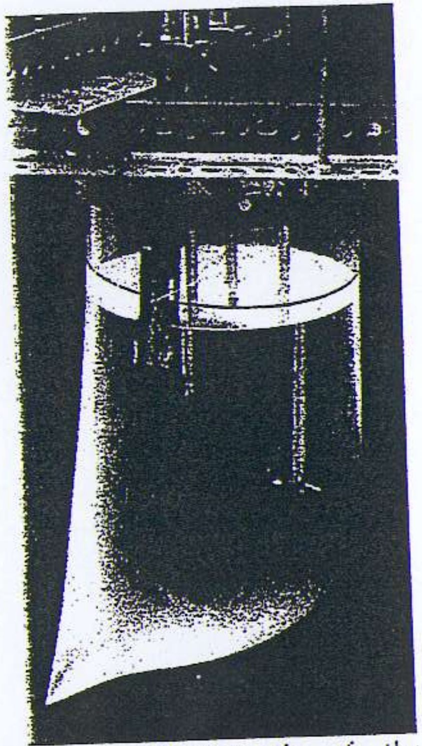

Fig. 1. Photograph of the experimental system showing, from left to right in the bag, the light scattering sensor, transmitting and receiving hydrophones, and the stirrer. The diameter of the bag is 235 mm.

The decay rates were determined by applying the method of integrated impulse response (IIR) [3] 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. The slope of the IIR 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 involved performing the IIR analysis at each of the desired frequency bands. The raw data were filtered after acquisition using a Butterworth bandpass filter in 10 kHz bands over the frequency range of 50 - 150 kHz. Above this frequency, the IIR 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.

Particulate absorption is a relatively small quantity to measure. The bag system was chosen after initial tests showed excessively high decay rates in other containers. These preliminary tests were carried out on a much larger volume of water (0.675 m³) in a large plastic tank and also using a glass tank with a similar volume of water as is used in the bag (around 0.016 m³). It became clear that to maximise the reverberation time, the boundary had to approximate as near as possible a pressure release surface around the whole volume. The free surface at the top of the volume is as close as one can get at atmospheric pressures. The walls of the bag are thin, certainly in terms of the wavelengths under consideration, and there is very little acoustic impedance mismatch. Hence, it is reasonable to assume that the walls will move in phase with the water and be virtually acoustically transparent. If all of the boundaries are thus assumed to be effectively air-water interfaces, it would be expected that the losses at the boundary will be due to sound transmission to the surrounding air. Considering a diffuse sound field, the power transmission coefficient for oblique incidence, θ_i, where the angle of transmission, θ_t, is always real for propagation from water to air is given by [4]

$$T_{\Pi} = \frac{4(\rho_a c_a \;\; \rho_w c_w)\cos\theta_t \; \cos\theta_i}{((\rho_a c_a \;\; \rho_w c_w)+\cos\theta_t \; \cos\theta_i)^2} \qquad (1)$$

where $\rho_a c_a$ and $\rho_w c_w$ are the specific acoustic impedances of air and water, respectively. Integrating this for angles of incidence from 0° to 90° gives the total power transmission coefficient of 0.0011, using typical values for the air and water properties at 20 °C. In order to test whether the losses were of this order, a series of measurements were made with different volumes of water and, hence, different ratios of the free surface to bag surface areas. Results for this work are presented in Section 3.1.

Two other sources of attenuation were evident from the early experimental results. First, the hydrophone mounts, which consist of a steel tube, altered the response characteristics of the volume. Second, the need to stir the solution to maintain the suspension introduced a degree of turbulence as well as mean rotational flow. To be consistent in the measurement technique the particulate-free solution was also stirred. Differences were observed between the calm water and the stirred water. These results are discussed in Sections 3.1.1 and 3.2.2.

3. Results

3.1 Boundary losses

The losses at the boundaries were determined indirectly by varying the volume of pure water in the bag. The reverberation time was recorded at a number of different volumes (see Fig. 2). The surface area of the bag was measured and the open area at the top of the volume was calculated by measuring the major and minor axes, taking the area to be of elliptic form.

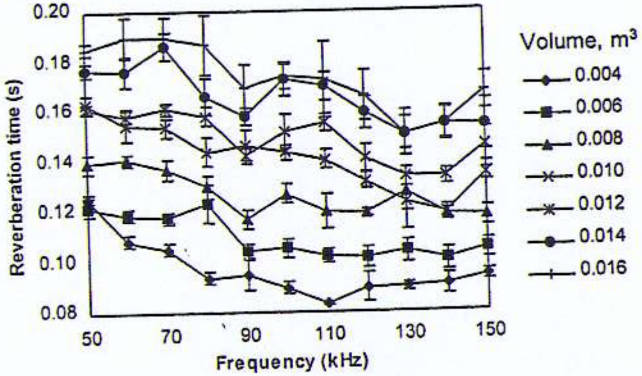

Fig. 2. Reverberation times for various volumes of water. Error bars represent ± one standard deviation from 30 measurements at each volume.

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 [6]

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

where V is the volume (m^3), 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, m^2, where S is the surface area of the volume (m^2) 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. The boundary absorption is given by

$$A = S_a\bar{a}_a + S_b\bar{a}_b \tag{3}$$

where the subscripts a and b refer to the air-water and bag-water interfaces, respectively. The water is assumed to have the ideal attenuation as described by Fisher and Simmons [5]. This assumption must be made as there is no independent method of determining the water's attenuation. The value of the air-water absorption coefficient, $\bar{a}_a$, was varied in order to minimise the variation between the bag absorption coefficient, $\bar{a}_b$, obtained from the reverberation measurements at each volume. A value for $\bar{a}_a$ of 0.015 gave a mean value for $\bar{a}_b$ of 0.0093 with a standard deviation over all volumes of 0.001. The variation with frequency of this test is shown in Fig. 3.

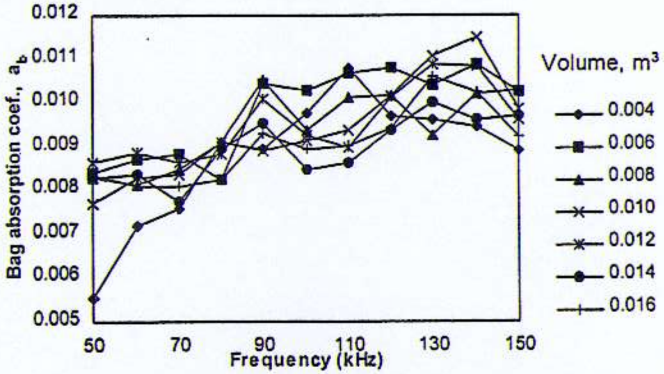

Fig. 3. Bag absorption coefficient, $\bar{a}_b$, at various volumes using the optimal value for the air-water interface absorption coefficient, $\bar{a}_a$, of 0.015.

The values for the attenuation coefficients $\bar{a}_a$ and $\bar{a}_b$ are an order of magnitude greater than the transmission coefficient given by Eq. (1). More curiously, the value for the air-water interface is greater than that for the bag-water interface by about 60 %. The reasons for this are not clear and require further experimental and analytical work. One possible cause was thought to be the viscous losses in the acoustic boundary layer. However, because the surfaces are pressure release, the phase inversion that occurs at the boundary when an incident wave is reflected means that the net tangential velocity is close to zero and, hence, there is no mechanism for viscous shear losses in this region. There will be a non-zero tangential velocity in the air surrounding the volume, but the magnitude of any losses through this mechanism are thought to be negligible.

3.1.1 *Mounts*

One possible transmission path out of the system is through the hydrophone mounts. These consist of metal tubes through which the hydrophone lead is passed. The hydrophone is located at the end of the tube but allows the tube to be filled with water to the same level as in the bag. Fig. 4 shows the reverberation times with and without the mounts present. Without the mounts, the hydrophones were simply suspended in the water. The hydrophones were also repositioned within the volume between the tests. Five reverberation times were taken at each position and the standard deviation is shown as error bars in the figure, although in most cases this was less than 2%. The most significant variation observed was for the case were mounts were used but one of the transducers was only a centimetre from the bag wall (mounts A). The mounts would appear to have an effect but this must be tempered by the advantages of keeping the hydrophone position fixed throughout the test.

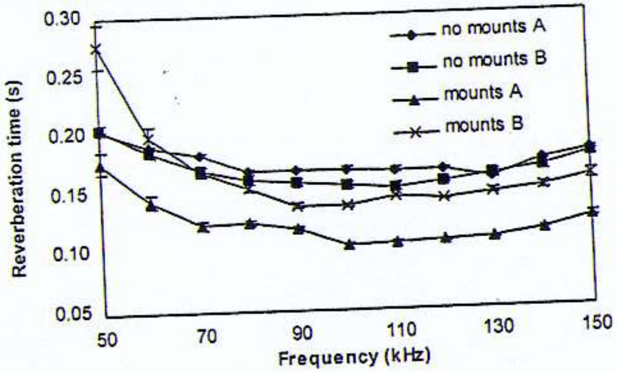

Fig. 4. Comparison of reverberation times with and without the hydrophone mounts.

3.2 Volume losses

3.2.1 *Particulate attenuation*

The principle aim of this study has been to determine the attenuation losses due to suspended particulate solutions. Results for various concentrations of spherical glass spheres with a mean particle diameter of around 40 µm are shown in Fig. 5. It should be noted that the attenuation has been normalised with respect to the particulate concentration. Agreement with the theoretical prediction [1] is good for the higher particle concentrations. At lower concentrations, when the effects of the particulate is slight, the agreement is less good and it is, in part, because of this that the other, more significant, loss mechanisms within the system require clarification.

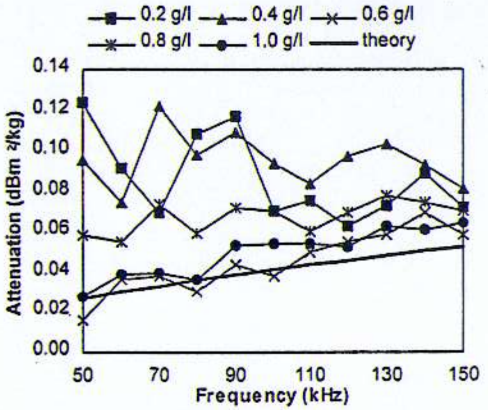

Fig. 5. Normalised particulate attenuation for various concentrations of glass spheres compared with the theoretical prediction.

3.2.2 *Turbulence*

To keep the particulate in suspension during tests, the solution is stirred by a mechanical stirrer (see Fig. 1) which generates significant turbulence. Reverberation times were measured for calm, particulate-free water and then after the water had been stirred as for when particulates are present. This was important as the particulate-free reverberation time is the reference signal for the subsequent tests with the particulate. As the solutions required stirring, it was important to ascertain what effect, if any, stirring the water had on the acoustics of the water volume. Figure 6 shows the difference in reverberation time for the calm and turbulent water. There are important differences between the two curves, even though there is also a large amount of scatter as indicated by the error bars. The turbulent response is generally flatter suggesting, perhaps, that the water turbulence or bulk motion of the water after stirring disrupts strong reverberation modes in the bag. At higher frequencies the reverberation times are greater than for the calm water which implies the stirring is a source of acoustic energy or that it reduces the dissipation from some loss mechanism. The effect of turbulence is of particular interest but the acoustic data need to be correlated to measurements of the scale, in terms of dimension and severity, of the turbulence itself.

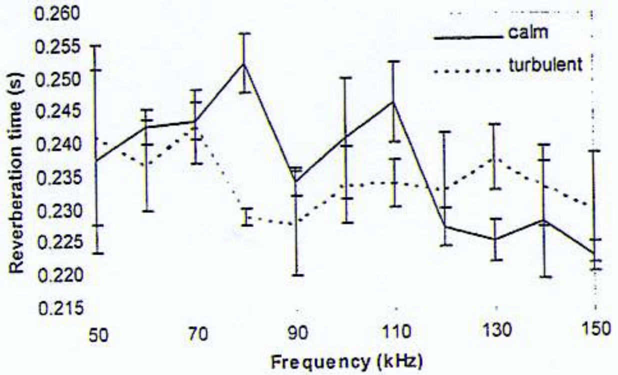

Fig. 6. Reverberation times for calm water and turbulent water. Error bars are ± one standard deviation from three measurements.

3.2.2 *Bubbles and dissolved oxygen*

One of the reasons turbulence may affect the acoustic behaviour is the affect the stirring has on dissolved oxygen and/or bubbles in the water. It is well known that bubbles are strong dissipaters of acoustic energy [7] but in order to calculate the effect of bubbles the bubble population and size distribution must be measured or estimated. The dissolved oxygen level has been measured throughout tests. It has risen gradually with time, regassing by natural resaturation of the water, affected by stirring. The water was degassed in a vacuum chamber prior to testing though the level of dissolved oxygen was in the range 40-61% when the measurements were taken.

6. Conclusion

A number of interesting phenomena have been observed when performing reverberation tests on a volume of water surrounded by near-perfect pressure release surfaces. Whilst the aim of the study is to measure the attenuation due to suspended particles, which it has been shown is possible for reasonable concentrations of particulate, the excess attenuation of the system appears to be due to as yet unidentified loss mechanisms associated with the boundaries or volume effects due to turbulence or the presence of dissolved oxygen. The losses at the free surfaces are an order of magnitude greater than those predicted by the classical pressure release boundary. This has important consequences for the study of the acoustics of the atmosphere/ocean boundary.

Acknowledgements

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