PROJECTOR SENSITIVITY MEASUREMENTS IN REVERBERANT FIELDS

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ABSTRACT

The measurement of transducer transmitting sensitivity is normally performed under free-field conditions. In laboratory tanks this is often achieved by using a time gate to isolate the direct signal from reflected signals. However, for high Q, low frequency projectors, the free-field time available in most laboratory tanks may be too short. Therefore measurements have to be made in the presence of a reverberant field. Here one technique of extracting the direct field is investigated by plotting the variation of pressure squared against the reciprocal of distance squared. The gradient of this graph is proportional to the acoustic power radiated into the tank and from this the direct field pressure and projector sensitivity can be calculated.

1. INTRODUCTION

Projector sensitivity calibration requires the measurement of transmitted pressure for a known voltage applied to the transducer. The transmitted pressure is usually determined using a calibrated hydrophone and its sensitivity curve. Once the pressure is known at an arbitrary range the pressure at one metre can be calculated and hence the projector sensitivity. This type of measurement is normally performed under free-field conditions (where no reflections are present). In laboratory tanks a time gate can be used to isolate the direct signal from the reflections so that the measurements can effectively be made under free-field conditions. The time available between the arrival of the direct path signal and first reflection at the hydrophone is called the 'free time'. The pulsed signal must have finished, or reached a steady state, in this time interval if the result is not to be contaminated by reflected signals. However, high Q low frequency projectors require free-times greater than those available in most laboratory tanks. Measurements can be made in very large tanks to overcome this problem but these are prohibitively expensive. Alternatively 'sea trials' can be undertaken but these are also very expensive, so a solution is needed using laboratory sized tanks. It is, therefore, interesting to consider the possibility of making measurements under reverberant conditions, similar to those used in airborne acoustics.

When free times are needed which are greater than those available in the laboratory tank there is no advantage in using pulsed signals [1] and measurements might as well be made with continuous wave signals. The use of continuous waves means that there is a build up of reflected waves giving rise to a reverberant field. When pressure measurements are taken in the presence of the reverberant field the resultant field is a superposition of the direct and reverberant fields. Simple measurements of the total field will give a false estimate of the direct field pressure and, therefore, sensitivity. The direct field can, however, be extracted from these measurements by measuring the acoustic power in the tank. In this paper we describe a series of preliminary measurements to investigate this technique.

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2. THEORY

The projector sensitivity is defined by:

$$S_p = 20\log_{10}\left(\frac{pr}{V_p}\right) \quad \text{dB re 1 µPa/V at 1 m,} \tag{1}$$

where S_p is projector sensitivity, p is the pressure (in µPa) generated by the projector at a distance r and V_p is the potential applied across the projector [2,3].

The hydrophone sensitivity is defined by:

$$S_h = 20\log_{10}\left(\frac{V_h}{p}\right) \quad \text{dB re 1 V/µPa,} \tag{2}$$

where S_h is hydrophone sensitivity, V_h is voltage received from the hydrophone and p is the pressure (in µPa) incident on the hydrophone [2,3].

It is known that the pressure in an enclosure is due to two fields, the direct (initial) field and the reverberant (reflective) field [4]. If the direct sound field is assumed to be radiated uniformly in all directions then the direct sound pressure P_d at a distance r from the sound source is given by

$$P_d^2 = \frac{\rho_0 c Q}{4\pi r^2} \tag{3}$$

where Q is acoustic power radiated by the source, ρ_0 is the volume density of the fluid and c is the speed of sound in the fluid [4]. The equilibrium value of the spatially averaged reverberant sound pressure P_r is given by

$$P_r^2 = \frac{4\rho_0 c Q}{A} \tag{4}$$

where A is the total sound absorption of the chamber [4]. Combining the equations (3) and (4) for the direct and reverberant sound fields (incoherently), gives the total pressure at a point in the sound field as

$$P^2 = \rho_0 c Q\left(\frac{1}{4\pi r^2} + \frac{4}{A}\right). \tag{5}$$

Now consider a projector radiating sound in to a tank and a hydrophone placed at a distance r from the this source. If measurements of pressure are made at different separations r, then a graph of pressure squared against the reciprocal of separation squared can be plotted [5] & [6]. From equation (5) it can be seen that the gradient, m, and y-intercept, C, of this graph are defined as follows:

$$m = \frac{\rho_0 c Q}{4\pi} \tag{6}$$

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and $$C = P_r^2 = \frac{4\rho_0 c Q}{A}. \qquad (7)$$

From equation (6) it can be seen that the acoustic power radiated into the tank can be found from the gradient of the graph. From this value of power and equation (3) the pressure at a separation r can be calculated. This is the pressure due to the direct field only and can be used for sensitivity calibration purposes.

This method of extracting the power and, therefore, the direct field is only accurate if the reverberant field is diffuse. If the reverberant field is not diffuse the residuals of the gradient are not evenly distributed about the true gradient and can result in an error in the value of power. However a diffuse field distributes the residuals well, virtually cancelling out the reverberant field error in the gradient (direct field). To obtain a diffuse field many reflections are needed [4] and therefore the tank needs a long reverberation time. The spatially averaged reverberant field pressure, *Pr*, will therefore be large for a diffuse field but will ensure an accurate determination of the gradient. In practice the reverberant field is made more diffuse by driving the projector with a noise source which excites the modes of the tank fairly evenly.

The reverberation time of the tank, T_r, is given by

$$T_r = \frac{0.161V}{A}, \qquad (8)$$

where V is the volume of the water in the tank and A is the total absorption of the tank and is given by

$$A = \sum_i S_i a_i, \qquad (9)$$

where S_i is the ith surface area and a_i is the ith absorptivity of the boundary of the tank [4]. To obtain a long reverberation time and hence a diffuse field it is therefore necessary to have a large volume of water and a small absorptivity at the boundaries of the tank.

3. EXPERIMENTAL SET UP AND PROCESSING OF DATA

The experimental system, as shown in figure 1, consists of a 100 kHz white noise continuous wave signal used to drive the projector producing a diffuse reverberant field in the tank. The signal sent to the projector is also sent to a digital oscilloscope where it is recorded for use in calculating the projector sensitivity. The hydrophone measures the pressure at its position in the tank, and its output is amplified before being recorded using the digital oscilloscope. This amplification ensures an adequate signal to noise ratio for the received signals at the oscilloscope.

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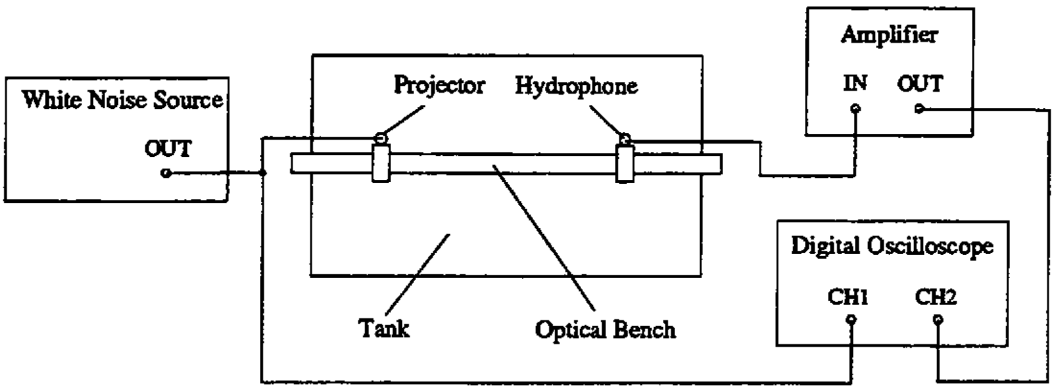

Figure 1: Experimental system.

The received hydrophone signals were recorded and saved to disk for a series of projector/hydrophone separations. Each record contained 50,000 points, sampled at 4 µs, giving a total record length of 200 ms. This sampling time gives a Nyquist frequency of 125 kHz which is appropriate for a maximum frequency of 100 kHz in the transmitted signal.

In order to process the data each record was divided into 50 sections of 1000 points each, to give a section such as that shown in Figure 2. A Fast Fourier Transform was then carried out on each section to give 50 noise spectra. The mean of these spectra was then taken to give the mean voltage spectrum of the received hydrophone signal. Averaging the noise spectra in this way helps to reduce the variance of the spectra. The same process was used to analyse the voltage applied to the projector. The hydrophone voltage spectra were converted to pressure spectra using the hydrophone calibration curve which gave the sensitivity as a function of frequency.

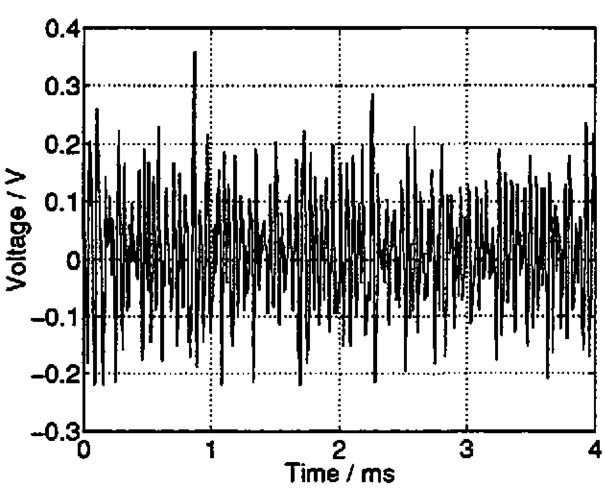

Figure 2 : Time series plot of voltage received by the hydrophone at a range of 32 cm from the ITC1001 projector in tank 3.

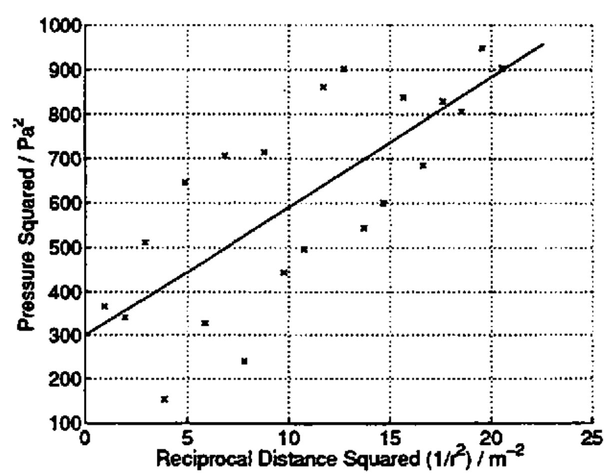

Figure 3 : Graph or pressure squared against the reciprocal of separation squared for the bandwidth 29.05 kHz to 29.30 kHz in tank 3.

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The power transmitted in any frequency band can be determined from the graph of pressure squared, for that frequency band, against the reciprocal of separation squared. An example of this for one frequency band is shown in Figure 3. The gradient of the graph is proportional to the acoustic power radiated into the tank in that frequency band. From the power radiated in each frequency band the pressure at one metre is calculated using the formula for the direct field, assuming uniform radiation. This, together with the spectrum for the projector drive voltage, enables the transmission sensitivity of the projector to be calculated. This is then compared with the free-field sensitivity of the projector which was determined previously by the National Physical Laboratory.

The sensitivity determined in this way is still influenced significantly by the reverberant field structure. This effect can be reduced by averaging the power data over a wider frequency range to obtain a smoother sensitivity curve. This was achieved by averaging the estimates of radiated power. An alternative approach would be to average the power spectra before taking the gradient of the pressure squared graph.

4. RESULTS

Measurements were made in four different tanks using two different projectors, an ITC1001 and an ITC1032. Tank 1 is made of polypropylene, 2.0 by 1.5 by 1.4 m in size, held together with steal body bands encapsulated in polypropylene. Tank 2 is a concrete tank, sunk in to the ground, approximately 3.06 by 1.52 by 1.68 m in size. Tank 3 is a metal tank with a 9 mm thick polypropylene inner liner, 1.86 by 1.18 by 1.09 m in size. Finally tank 4 is made of 9 mm thick polypropylene, 2.72 by 1.51 by 1.32 m in size, held together with steal body bands encapsulated in polypropylene. The transmission sensitivity results determined from the acoustic power in the four tanks are shown in Figures 4 to 9. In all of the graphs the data points (x) denote the transmission sensitivity determined from acoustic power, whereas the solid line (—) denotes the reference data determined from free field measurements.

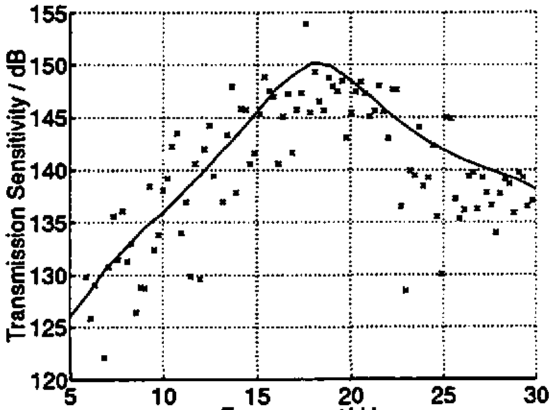

Figure 4 : Transmission sensitivity (dB re 1 μPa/V at 1 m) of the ITC1001 projector for a bandwidth of 244 Hz measured in tank 3.

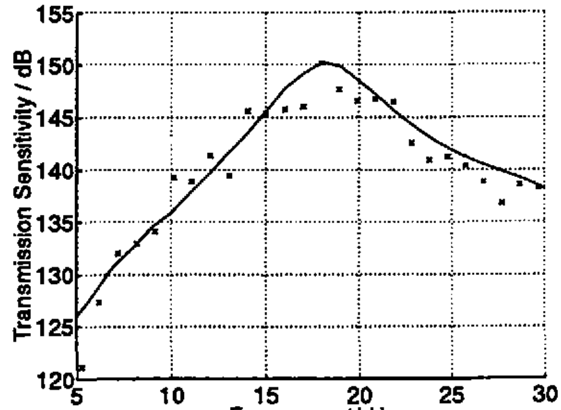

Figure 5 : Transmission sensitivity (dB re 1 μPa/V at 1 m) of the ITC1001 projector for a bandwidth of 977 Hz measured in tank 3.

Figure 4 shows the transmission sensitivity obtained using individual bands of 244 Hz. As can be seen, the data has a significant scatter but is distributed around the reference curve. However, when the data is averaged, in power, over a greater bandwidth the amount of scatter is significantly reduced with the points following the general shape of the curve. This is shown in Figure 5, which shows the same results as Figure 4, except that the transmission sensitivity is averaged over four bins (to give a bandwidth of 977 Hz).

The results for projector ITC1001 taken in all four tanks, using an average over approximately 1 kHz, are shown in Figures 5 to 8. The graphs appear to show that the transmission sensitivity results are below the reference sensitivity curve for tanks 1 & 2. The points fit quite well with the curve for tank 3 and the points are above the curve for tank 4. Figure 9 shows similar results obtained for the ITC1032 projector in tank 3; here the results and reference curve agree well, even better than for the ITC1001 projector in tank 3.

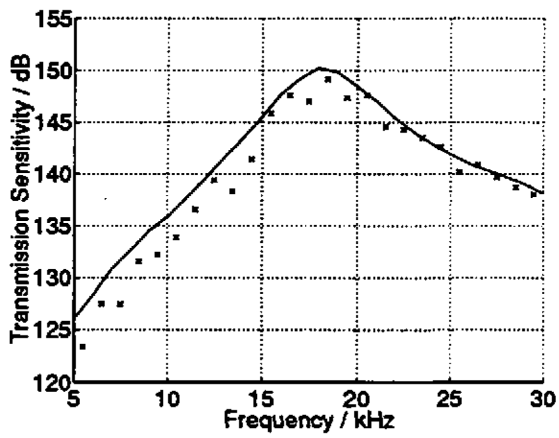

Figure 6 : Transmission sensitivity (dB re 1 µPa/V at 1 m) of the ITC1001 projector for a bandwidth of 1 kHz in tank 1.

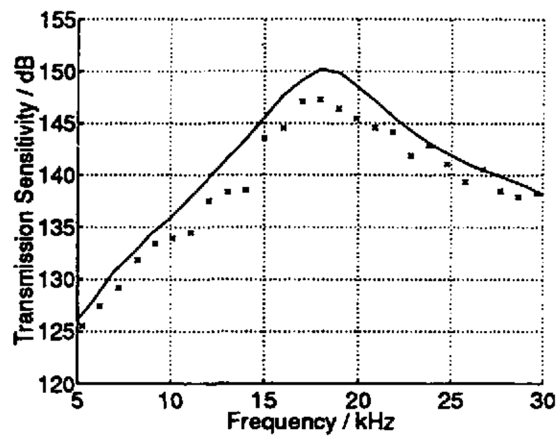

Figure 7 : Transmission sensitivity (dB re 1 µPa/V at 1 m) of the ITC1001 projector for a bandwidth of 977 Hz in tank 2.

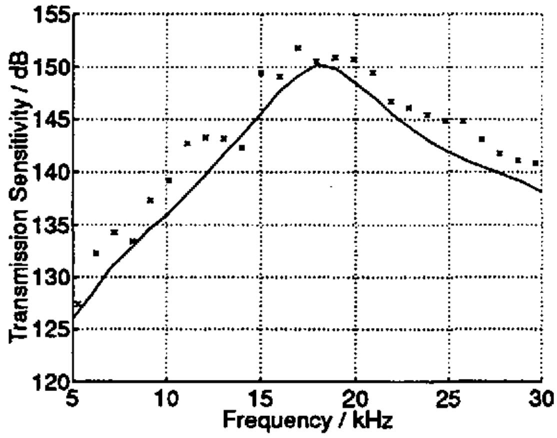

Figure 8: Transmission sensitivity (dB re 1 µPa/V at 1 m) of the ITC1001 projector for a bandwidth of 977 Hz in tank 4.

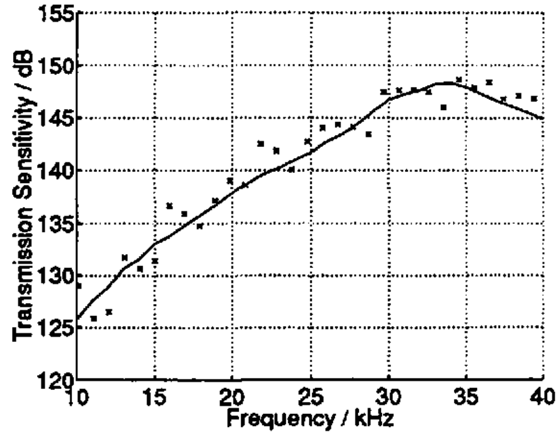

Figure 9 : Transmission sensitivity (dB re 1 µPa/V at 1 m) of the ITC1032 projector for a bandwidth of 977 Hz in tank 3.

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The differences between the reverberant field and free-field calibrations have been investigated as follows. Firstly the difference between the two calibrations was calculated on a point to point basis and then averaged over the whole frequency range. This gives the average difference, or systematic shift, between the two curves in dB. The results of this analysis are shown in Figures 10 and 11 for the two projectors and four tanks using bandwidths of approximately 250 Hz and 1 kHz respectively. (The bandwidths are actually 250 Hz and 1 kHz for tank 1, and 244 Hz and 977 Hz for tanks 2 to 4.)

Projector	Tank 1	Tank 2	Tank 3	Tank 4
ITC 1001	-2.1	-2.6	-2.7	1.3
ITC 1032	-2.3	-3.3	-0.7	-0.2

Figure 10 : Mean difference (in dB) between the reverberant field and free-field calibrations for a bandwidth of approximately 250 Hz for the four tanks and two projectors.

Projector	Tank 1	Tank 2	Tank 3	Tank 4
ITC 1001	-1.5	-2.1	-1.1	2.1
ITC 1032	-2.0	-3.1	0.3	0.5

Figure 11 : Mean difference (in dB) between the reverberant field and free-field calibrations for a bandwidth of approximately 1 kHz for the four tanks and two projectors.

5. DISCUSSION

The results presented in Figures 4 to 8 indicate that the trend of the reverberant field calibrations generally follow that expected from the reference free-field calibrations. Clearly there is a significant scatter in the 250 Hz bandwidth results, but those for a 1 kHz bandwidth have a much smaller scatter with a range of about ± 2 dB. On some of the graphs there is potential evidence of a periodicity in the fluctuations (especially Figures 7 and 9) which may be related to the modal structure within the tanks. The results shown do indicate mean shifts or offsets from the reference results. The graphs, and Figure 11, indicate that these are largest for tanks 1 and 2, while they are of the opposite sign for tank 4. It is not understood why this is so and further work needs to be done to understand this.

As was mentioned earlier, in order to obtain an accurate result for the transmission sensitivity from power measurements an accurate determination of the gradient of the pressure squared against the reciprocal of separation squared graph is needed. To obtain an accurate gradient requires a diffuse, reverberant field so that the residuals of the gradient cancel each other out evenly, leaving just the original gradient due to the direct field.

The projectors ITC1001 and ITC1032 are fairly omnidirectional, however the ITC1001 varies by approximately 0.5 dB with direction and the ITC1032 varies by approximately 1 dB with direction. This will produce a slightly less diffuse reverberant field and therefore introduce an error in the gradients of the graphs.

It is interesting to consider the relative suitability of the tanks used for this type of measurement. Tank 1 has a volume of 4.2 m^3, tank 2 a volume of 7.82 m^3, tank 3 a volume of 2.39 m^3 and tank 4 a volume of 5.41 m^3. Given that the larger the volume of water the greater the reverberation time of the tank and so the more diffuse the reverberant field, it would be expected that the amount of scatter on the reverberation calibration results would be less for larger tanks. Conversely for a highly absorbent tank it would be expected that the amount of scatter on the graphs would be large. To test this the reverberant field level in the tanks was measured, a higher reverberation level indicating a longer reverberation time. Tank 3 appears to have a reverberant field level approximately 20% higher than tank 2, and tank 4 has a field level approximately 15% higher than tank 3. It would be expected that tank 2 has a lower reverberant field level, despite its larger volume, due to the higher absorption of its concrete walls which are coupled into the earth. Also tank 4 would be expected have a higher reverberant field level than tank 3 as a result of its larger volume. Therefore, the amount of scatter on the sensitivity graphs would be expected to be greatest for tank 2 and least for tank 4. However the scatter of the results on the sensitivity graphs do not show any particular trend. This may be due to the limited range of reverberation times of the tanks tested so far. The reverberant results, averaged over approximately 1 kHz, are in better agreement with the free field results than with those averaged over 250 Hz. This is assumed to be due to the effect of standing waves in the tank cancelling each other out when averages are taken over a wider bandwidth.

6. CONCLUSIONS

The results seem to indicate that this method has significant promise but is not yet a very accurate method of determining projector sensitivity. Using a more diffuse field seems to improve the accuracy as does averaging over a wider bandwidth which tends to cancel out the effects of the standing wave modes of the tank. It is intended to pursue this technique with a detailed study to investigate the influences of the tank size, shape and construction, as well as processing techniques. The potential advantages of making multiple scans and using longer data sequences will also be investigated. Overall the aim is to determine the potential of this technique and how it is influenced by the modal structure of the tank.

7. ACKNOWLEDGEMENTS

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COMPARISON OF TRANSDUCER RESPONSE IN A FREE FIELD AND IN A TANK USING FINITE/ BOUNDARY ELEMENT MODELS.

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Finite and boundary element modelling techniques can be used to accurately predict the response of transducers vibrating either in the free field or in tanks. Near field pressures and admittances are computed for steady state vibration of a ring transducer in a cylindrical tank and a flextensional transducer in a rectangular tank and compared with corresponding free field results. The effect of altering the absorbent properties of the tank walls is also studied. Calculations of this type can be used to assess the suitability of a tank for calibrating different types of transducer.

NUMERICAL CHARACTERISATION OF A REVERBERANT TANK FOR CALIBRATION MEASUREMENTS

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Despite the presence of anechoic linings, scattered and reverberant fields produce significant error in calibration of low-frequency projectors in tanks, if a free-field environment is assumed. In addition to a general loss of accuracy because of the presence of scattered waves, measurements become sensitive to the position of source and receiver in any standing wave pattern set up in the tank - in a manner which varies with frequency in a complex fashion.

Until recently the only practical means of overcoming these problems was to repeat any measurements at a number of "randomly chosen" orientations and positions within the tank, in the anticipation that some form of averaging of the errors could thereby be obtained. However, with advances in theoretical understanding and in computing capability, it has been suggested that a numerical model of any specific tank can be created, which would allow the correction of any specified measurement configuration to an effective free-field calibration.

This paper attempts to assess the feasibility and utility of such an approach, identifying the difficulties and errors involved - in particular those associated with modelling the various different boundaries of the water volume, and of creating a single mesh appropriate to a wide range of frequencies. In parallel, the errors and limitations of the multiple averaging approach are investigated theoretically. It is demonstrated that the "law of diminishing returns" rapidly sets in for either approach, and an effective limit of achievable accuracy in calibration is derived.