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AN ACCURATE METHOD FOR THE MEASUREMENT OF TARGET STRENGTH

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1.0 Introduction

This paper describes a procedure for the accurate measurement of the acoustic target strength of small targets under laboratory conditions. It was developed during the course of an investigation into the possible use of table-tennis balls as standard targets for the calibration of sonars used in fish stock assessment (1), and the technique was also used for the investigation of the resonances of tungsten carbide balls which are favoured in some establishments as primary standards (6). The frequency now used for acoustic surveys of fish is 38 kHz, but measurements were also done at 30 kHz, which was used previously in some places. An extensive series of measurements was made on a number of table-tennisballs, with the result that the repeatability of the measurements could be assessed, and the possible accuracy could be considered in detail. The resonances in the tungsten carbide balls were around 90 kHz, for which different transducers were used, but the technique was identical to that used for the lower frequencies.

2.0 The measurement of target strength

2.1 Basic principles

The fundamental idea is to compare the echo voltage Vt from the target at a range Rt with that Vs from the surface, acting as a plane reflector, at a range Rs, the general arrangement of the target and the transducers being shown in fig.1 These four are the only quantities that need to be measured; there is no need for the transducers to be calibrated separately. The drive to the transmitting transducer need not be measured, but it must remain constant for the two measurements of voltage; if however it is kept constant over a long series of measurements, then Vs should also remain constant for a given Rs, and this acts as a guide to the overall stability of the equipment. For a target of strength TS dB. and for a source level of SL dB. relative to some reference at a range of 1 m., then on applying the sonar equation and ignoring absorption and anomalous propagation (this is justified for the very short ranges being used), the target echo level is given by:

$$ELt = SL - 40 \log Rt + TS \qquad (1)$$

For the echo from the surface of the water, the receiving transducer is in effect 'looking' at the transmitter at a range 2Rs, since the surface acts as an ideal plane mirror, and so on applying the sonar equation for direct transmission the surface echo level is given by:

$$ELs = SL - 20 \log (2Rs) \qquad (2)$$

The difference in voltage levels equalsthe difference in acoustic pressure levels, and thus by eliminating the source level from the two equations and re-arranging:

$$TS = 20 \log (Vt/Vs) + 20 \log (Rt^2/2Rs) \qquad (3)$$

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In the practical use of the pulsing equipment the ratio Vt/Vs is measured by a combination of differences in gain settings in steps of 10 dB. and the ratio of voltages in the range 0.3 to 1.1 V. The correct measurement of the range is discussed below.

The measurements of target-and surface-reflected signals are made in quick succession, and it was originally assumed that the presence of the ball did not interfere with the transmission of sound to and from the surface. However, it was found that there was a significant scattering by the ball, giving a loss of about 0.6 dB. on average for a table tennis ball and a gain of around 0.1 dB. with a tungsten carbide ball. Therefore measurements of the surface echo were made both with the ball absent (for the calculation of target strength) and with it present, comparison between the two giving the apparent forward scattering loss or gain for the two-way path. The necessity of measuring the surface echo in the absence of the ball requires more care inmonitoring the transmitter drive level because of the additional time interval between measurements while the ball is inserted or removed.

2.2 The definition of range

There are a number of considerations here. Firstly with regard to units, it will be noted that in equation (3) the factor involving the ranges has the dimensions of length and therefore the choice of units for Rs and Rt is important. The ranges must therefore be measured in metres in order to make equation (3) consistent with the usual definition of the target strength of a sphere (ref.3, chap.9). The second consideration concerns the correct point on the ball to which the range should be measured. In the ideal case, for a target the diameter of which is large in wavelengths and for incident plane waves, specular reflection from the surface can be assumed, and the reflected waves then appear to spread from a point midway between the surface and the centre of curvature (ref. 3, p.267). If the incident waves are spherically spreading rather than plane, the reflected waves appear to come from a point nearer to the surface, but it can be shown that the shift is less than 1% of the diameter of the sphere if the radius of curvature of the wavefront is greater than seven sphere diameters. In the definition of target strength in terms of incident and reflected intensity, the incident intensity is that at the surface of the ball, whereas the reflected energy is spreading from a point within the ball; since the offset is small compared with the range and both transducers are at the same range, it is a fair approximation to take the average range as the range to the surface of the ball plus one eighth of the diameter.

The final point concerns the point at the transmitting transducer from which the outgoing spherical acoustic waves appear to spread; this is important for applying the inverse spreading law accurately. If spherical spreading occurs from the face of the transmitting transducer, the product of received voltage (for constant transmitting voltage) and range should be constant. If the reciprocal of the voltage is plotted against range, the result should be a straight line passing through the origin; if on the other hand the range is measured between the wrong points, the error is indicated by the offset on the range axis for 1/V=0. The measurements had to be made without changing the gain of the receiving amplifier, since an error of 0.1 dB. in an assumed change of 10.0 dB. would cause a noticeable offset in the plot. A typical plot of 1/V against range at 30 kHz is shown in fig.3, and this indicates that the spreading loss behaves in accordance with theory over the variation in range appropriate to the experimental arrangement; using linear regression analysis for accuracy, the offset is 21 mm., the spreading centre being behind the face of the transducer. The range shown is one half of the effective distance between transducers, and therefore the effective offsets is 42 mm.; this should be applied to the transmitter alone, i.e. the centre of spreading is properly located this distance behind the face of the transducer. In the formula for target strength the term 2Rs appears, so that the double offset is automatically included, if Rs is corrected by the single offset. For the term Rt^2, this is properly the product of the range from the transmitter to the target and that from the target to the receiver; since the offset is small compared with the range, it is sufficiently accurate to divide the double offset equally between the transmitting and receiving ranges, i.e. to include in each the calculated offset relative to the distance to the surface; thus Rt is corrected by the calculated offset in Rs. The calibration method is sensitive at the 0.1 dB. level to changes in the directional response, so that the change in the direction of the ray path from transmitter to receiver as the range changes (due to the horizontal separation of the tranducers) is automatically taken into account, and this effect may be a cause of the offset.

3.0 Instrumentation

3.1 The Mounting Frame

This was designed to support the transducers firmly in relation to the ball and to the surface of the water, and the general arrangement is shown in fig.1. The horizontal bars, 3.0 m. long, are slotted steel angle, and the vertical sides, 2.4 m. long, are aluminium tube, with square aluminium blocks at the corners. In use the top bar rests across the wooden beams covering the tank, and the whole assembly can be lifted on an overhead crane. The overall size is limited to that which could be handled conveniently in the tank laboratory, the main constraints being the width of the tank and the clearance height over the covering boards. In consequence the range from the transducers to the ball was rather short at 1.2 m. maximum, and this makes the accurate specification of range, as discussed above in section 3.2, very critical. The advantages of this inverted arrangement, in addition to permitting the surface to be used in the continuous calibration of the transducers, are that the transducers do not have to be brought out of the water while the target is changed and that air bubbles are less likely to collect on their faces.

3.2 The Transducers

For the lower frequency measurements these were a pair of separate 30 kHz units, each comprising a "sandwich" element with an active face diameter of 31 mm. mounted in a housing 63 mm. square. As part of the attempts to reduce the local reverberation the sides and faces of the housings were covered in closed-cell foam neoprene, leaving only the active face exposed; for the same reason the transducers are spaced 150 mm. apart.

The transducers have a loaded Q of 3.5, and the bandwidth is adequate for use at 38 kHz; the transmitting one has a tuned transformer matching it to 50 ohms at 30 kHz, and this is a suitable load for the driving amplifier. The receiver is also tuned, but matched to 10 Kohms, the input resistance of the receiving amplifier; in this way the bandwidth on reception is maximised. The two transformers are mounted in the same metal box, and this gave rise to some additional cross-talk, which was minimised by not earthing the outer screen of the cable from the receiving transducer. Neither outer screen in any case made electrical contact with the water; one lead in each transducer is however connected to the front face, but it is insulated from the water by the anodised finish. The transformers are double wound, so that there is no direct connection from the earthy side of the electronics to the water, as it has been found that this arrangement minimises electrical interference.

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3.3 The pulsing equipment

The Acoustics Group's general-purpose pulsing system was used, with the addition between the main receiving amplifier and the receiver gate of a suitable filter. For 30 and 38 kHz second-order linear-phase bandpass filters (a separate one for each frequency) with a relative passband width of 0.2 (5) were used, and for 100 kHz a Butterworth type filter with a bandwidth of 40 kHz was used. These gave substantial improvements in signal/noise ratio while minimising the distortion of the envelope of the pulse. A block diagram of the system is shown in fig.2. On the transmitting side the pulse duration was 400 microsecs at intervals of 300 msecs; this slow repetition rate was necessary in order to allow the long-term reverberation to die down sufficiently. The drive to the transmit amplifier was monitored and kept at a convenient reference level to an accuracy better than 0.1 dB.

The receiver gate was set to sample the signal for about 160 μsecs, synchronised. The same sample duration was used consistently, so that any errors due to the sensitivity of the detector, including the sample-and-hold, varying with the mark/space ratio would be minimised. The sample-and-hold circuit uses an FET op-amp to permit the use of a long "hold" time constant and a short "sample" time constant, so that the accuracy of measurement is not affected to any significant degree by the on/off ratio.

4.0 Problems of reverberation

4.1 Air bubbles

The resonant frequency of an air bubble of radius r in water at atmospheric pressure is given by $kr = 0.013$, where k is the wave number $2\pi/\lambda$, λ being the wavelength in water (2). Hence the diameter for resonance is 0.21 mm. at 30 kHz, and 0.16 mm. at 38 kHz; bubbles of these sizes therefore have very much larger target strengths than expected simply from their diameter, and furthermore they would be slow to rise to the surface. Such effects were clearly seen when the frame was first put into the water; small bubbles were slowly released from the surface of the metal and as they floated up to the surface of the water they caused substantial reverberation, giving echoes comparable in magnitude to those from the target balls, although the air bubbles were almost too small to be seen. During a long series of experiments the transducers and the lower horizontal beam to which they were fixed were therefore kept continuously immersed.

4.2 Inter-element coupling and short-term reverberation

The mechanism for this effect is that acoustic energy is coupled directly from the transmitting transducer to the receiver through the water, and after the electrical drive ceases both transducers ring with a rate of decay that to a first approximation is set by the bandwidth. However energy is also coupled into the housings, and the behaviour of these cannot be deduced directly from the measurement of admittance, from which the bandwidth is usually calculated; there was also some electrical cross-talk causing a similar effect. The overall effect can be regarded as reverberation arising within the transducer assemblies, and the level of these signals must be more than 60 dB. below the direct signal via the surface (at a range of about 1.8m.) at a time between 1.0 and 1.5 msecs after the finish of the electrical drive. It is possible that some of these unwanted signals were in fact echoes from the discontinuities along the slotted angle forming the bottom of the frame. It was very difficult to reduce this reverberation to low enough levels, but acceptable results were eventually obtained by wrapping the housings in closed-cell foam rubber in order to stop radiation from everywhere except the active faces of the elements, increasing the spacing between the transducers to 150 mm. centre to centre, and putting in front a block of rigid plastic foam 150 mm. x 280 mm. x 15 mm. thick with cut-outs 50 mm. square, a little larger than the elements. No such arrangements could be made for the 100 kHz units, but in any case the unwanted signals decayed enough in a shorter time because of the higher frequencies.

4.3 Long-term reverberation

It is this which is the final limiting factor in the achievement of high accuracy in a small tank at low frequencies as compared with measurements in the open sea, but it is at least easy to overcome. The causes are the low absorption in fresh water and the low loss on reflection at the walls of the tank. The former is less than 0.001 dB./m. at 30 kHz and the latter, from one observation some ywars ago at 50 kHz, is less than 1 dB. per reflection at normal incidence. The cure is to wait between pulses for the reverberation to die down sufficiently. Originally an interval of 180 msecs was used, but with the improved sample-and-hold, intervals of 300 msecs could be used, and then the long-term reverberation became negligible compared with the short-term interference discussed above.

5.0 Assessment of overall accuracy

5.1 The measurement of voltage

There are two separate considerations here. The less difficult one is the linearity of the amplifiers and the detector, together with the resolution of the digital voltmeter. The linearity can be checked from the spreading loss calibration, since any gradual overload should show up as a departure from the ideal straight line at the higher signal levels; since no such trend was observed it was concluded that the overall linearity was good. The resolution of the meter was 1 mV. and the minimum signal was kept above 300 mV., and hence the discrimination was much better than 0.1 dB.; the transmitting level was set to a standard level to an accuracy of better than 3 mV. in 1000 mV., corresponding to a possible error of 0.03 dB.

The second consideration is the accuracy of the switched gain in the receiving amplifier, and this was a greater problem. The difficulty lies in the wide range of signal levels, the difference in level between signals from the target and from the surface being of the order of 40 dB. The gain changes were corrected by setting the individual 10 dB. changes accurately by using the detector and the digital voltmeter. It is probable that before these changes the error in a change of gain of 40 dB. was about 0.6 dB. in a direction to give an underestimate of target strength, but after the adjustments the cumulative error was of the order of 0.2 dB. In the course of this part of the work it was noted that errors due to overloading at the maximum output of the detector (1200 mV.) were probably less than 0.1 dB.

5.2 The measurement of range

The greatest accuracy is required in the range to the target, since it appears as Rt^2 in the formula for target strength. An accuracy of 0.1 dB, in target strength requires an uncertainty of less than 6 mm. in a range of 1 m.; a random error of 3 mm. is to beexpected. The greatest uncertainty is caused by the apparent offset in the centre of spreading from the transmitting transducer, but this should be reduced, if not eliminated, by the calibration procedure described above. Differences between the equivalent voltage level on the mean regression line of 1/V vs. Rs and the actual measured level are generally less than 0.1 dB.; on the other hand without the correction for the apparent offset, i.e. if the mean line was forced to pass through the origin, the errors could exceed 0.5 dB. The need for these corrections is an unfortunate consequence of the necessity of working with very short ranges.

5.3 The attainable accuracy in target strength

There are a number of considerations here, the most important being the distinction between resolution and absolute accuracy, and also that between short-term and long-term accuracy. The resolution on a short-term basis is set in respect of electrical measurements by the discrimination in reading the voltages and setting the transmitting level, and whether the gain needs to be changed between readings of the same quantity. The resolution in target strength is determined also by the repeatibility of the measurements of range, both to the target and to the surface, the fixed corrections to the actual measured distances being a source of systematic errors. The repeatability was of the order of 3 mm., and this corresponds to a resolution of 0.1 dB. in target strength.

The stability of the sensitivities of the transducers is only significant over short periods of time; short-term random fluctuations as measured by changes in the surface-reflected signal between successive measurements of target strength at the same frequency are of the order of 0.2 to 0.3 dB., but this includes purely electrical changes such as changes of gain with temperature. These fluctuations could be caused by air bubbles collecting on the faces of the transducers, but these problems were minimised by leaving the transducers fully immersed throughout most of the time during which the measurements were being done. Taking the resolution in the measurements of voltage into account, the relative accuracy in comparing target strengths is of the order of 0.15 dB. The absolute accuracy is affected also by the systematic errors which arise in the exact definition of range, as discussed in section 2.2, and in the accuracy of the gain as discussed in section 5.1, and the combined effect of these is that the absolute target strength is probably not accurate to better than 0.5 dB.

6.0 Results

6.1 Table tennis balls

The results have already been presented elsewhere, so only a brief summary is given here. The main point is that these balls are barely acceptable as standard targets at 30 kHz and totally unacceptable at 38 kHz. The mean target strength at 30 kHz for a random selection of 30 balls was -38.1 dB. with a standard deviation of 0.04 dB., and at 38 kHz it was -43.7 dB. (standard deviation 3.1 dB.). The reason for the wide variation at 38 kHz was that there was a mechanical resonance very close in frequency, and small changes in this, caused for example by the ball absorbing water, caused large changes in target strength; as an extreme example, a change of 9 dB. was observed over a week-end of continuous immersion.

6.2 Tungsten carbide balls

The aim of the investigation of the resonance around 90 kHz, which showed as a sharp null in target strength, was to examine whether differences in resonant frequency could account for small differences in target strength at 38 kHz. This work is being reported elsewhere (6), and it is mentioned here as another example of the use of this method of measuring target strength. The variation in target strength around resonance was measured on 14 balls for comparison between balls and with theory. The balls had been measured at 38 kHz both at Birmingham and by the Marine Laboratory at Aberdeen, but more variation was shown than expected; it was concluded that this was more likely to have been due to stray disturbances such as air bubbles trapped in the nylon monofilament holding the ball than to differences in mechanical properties manifesting themselves as changes in resonant frequency.

7.0 Acknowledgements

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8.0 References

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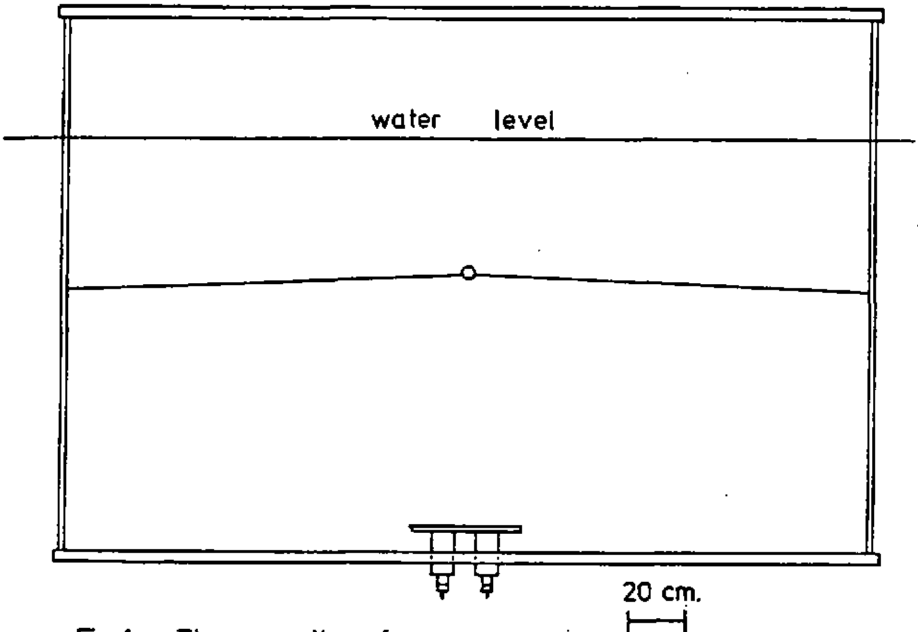

Fig. 1 The mounting frame

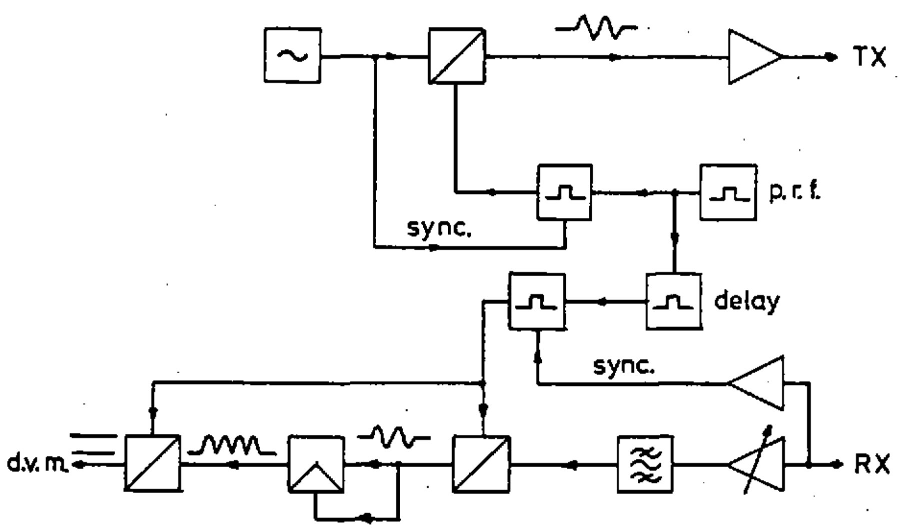

Fig. 2 Functional diagram of pulse-test equipment

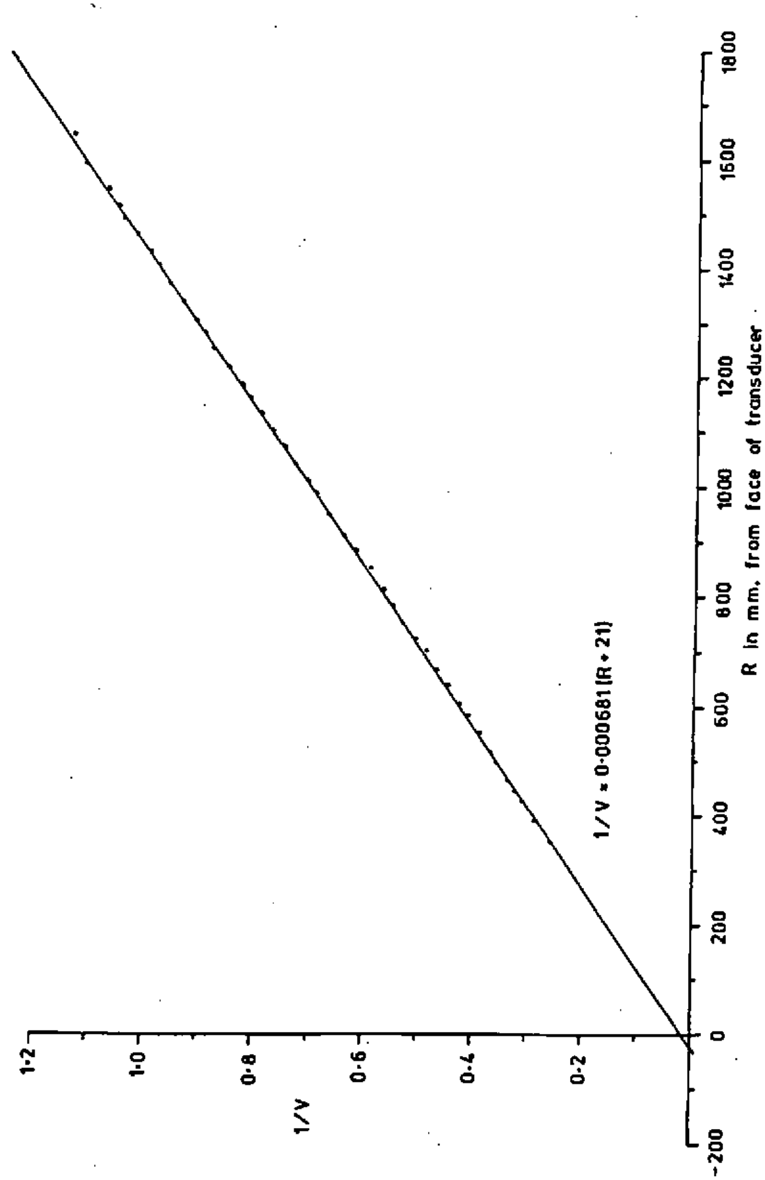

Fig. 3 Spreading loss calibration at 30 kHz