Proceedings of The Institute of Acoustics

TUNGSTEN CARBIDE CALIBRATION SPHERES

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INTRODUCTION

Echosounders may be calibrated by measuring the signal from a reference target whose acoustic scattering properties are known. Spheres made from tungsten carbide, copper and other materials have been used for this purpose [1].

Tungsten carbide is well suited to calibration work in the sea, being extremely hard and resistant to corrosion in salt water. Tungsten carbide spheres are commercially available as ball bearings. They are produced by sintering a powdered mixture of tungsten carbide with a nominal 6% cobalt added as a binder. The 38.1mm diameter sphere is a convenient size for calibrating the towed 38kHz transducers which are commonly used on acoustic surveys of fish stocks.

The accuracy of the calibration depends upon how well the acoustic properties of the reference sphere are known. Theoretical and experimental studies have been conducted to determine the calibration error, how it depends upon the physical properties of the sphere and environmental factors such as the temperature [2,3]. In this paper, we review earlier work on tungsten carbide spheres and describe new experimental results which have been used to derive confidence limits on the sphere target strength.

THEORY

The acoustic cross section of the homogeneous elastic sphere may be expressed as the product of the geometric cross section area and a function F of four parameters which describe the properties of the sphere and the surrounding medium [4]. For a sphere of radius a:

$$\sigma = \pi a^2 F(c1/c,\ c2/c,\ \rho1/\rho,\ ka) \qquad (1)$$

where $\rho1$, c1 and c2 are respectively the density, the longitudinal and the transverse sound velocities within the sphere, ρ and c are respectively the density and the sound velocity in the surrounding medium, $k=wa/c$ and w is the angular frequency. F is the square of the form function modulus. It may be evaluated by the numerical approximation of an infinite series of partial wave contributions, according to well established theory [2].

σ depends upon the frequency, as illustrated in Figure 1. It varies cyclically at low frequencies due to geometric resonances which occur even in the ideal rigid sphere [5]. Then, above some critical frequency, much sharper variations are caused by the sphere elasticity and coupling of mechanical vibration modes. The frequencies of these resonances are inversely proportional to the sphere diameter and they depend upon the sound velocity in the surrounding water. For σ to be insensitive to environmental changes, therefore, it is important to select the sphere size so that the echosounder frequency is far from any mechanical resonance of the sphere. In the case of the 38.1mm tungsten carbide sphere, the first mechanical resonance is at about 90kHz, well above the 38kHz frequency of the equipment to be calibrated.

Equation (1) applies to CW transmission at a single frequency. The scattering properties of a target insonified by a pulsed transmission are described by the effective cross section which is defined as a weighted average of the function F over the frequencies in the transmitted pulse [6].

$$\sigma_e = \pi a^2 \int_0^\infty F|S(w)H(w)|^2 dw / \left[\int_0^\infty |S(w)H(w)|^2 dw \right] \quad (2)$$

here S(w) is the spectrum of the transmitted pulse and H(w) is the frequency response function of the receiver, including the receiving transducer. The effective target strength (TS) is defined as usual to be

$$TS = 10*\mathrm{Log10}(\sigma_e/4\pi) \quad (3)$$

Thus TS is a property not only of the target, but of the complete echosounder and target system, and it will depend upon such parameters as the pulse length and bandwidth. However, provided that the echosounder centre frequency is well removed from any mechanical resonance of the target, the TS will depend mainly upon the target properties and the effect of small changes in the echosounder parameters will be negligible.

<u>Calculation of the target strength</u>

A theoretical value for the absolute TS may be obtained from (1-3), given numerical values for the physical parameters in the equations. The sphere diameter and density are simple to measure accurately, the sound velocities less so. MacLennan and Dunn [4] have shown how the longitudinal and transverse sound velocities within a sphere may be deduced from measurements of the mechanical resonance frequencies. Both the sound velocities have a significant dependence on the sphere density, due to the common dependence of the density and the sound velocities on the cobalt concentration. The sound velocities are estimated from the regression equations

$$c1 = 0.11\ (\rho 1 - 14900) + 6853\mathrm{m/s} \quad (4)$$
$$c2 = 0.18\ (\rho 1 - 14900) + 4171\mathrm{m/s} \quad (5)$$

which apply at 11deg. C. and, in the case of c2, the temperature coefficient is estimated to be -1.3m/s/deg. C. $\rho 1$ is the sphere density in kg/cu.m. Tungsten carbide with exactly 6% cobalt binder has a density close to 14900kg/cu.m. [7] and for this material, at 11 deg. C., the 95% confidence limits on the sound velocity estimates are c1 = 6853 $\pm$ 19m/s and c2 = 4171 $\pm$ 7m/s [4].

Substituting (4,5) in (1) eliminates the sound velocities from the target strength equations and TS may now be calculated from the density and other straightforward measurements. Table I shows the results obtained for two echosounder types, the EK400 scientific sounder as used by many institutes on fish stock surveys, and the Duich system which is used by the Aberdeen Marine Laboratory for fish target strength experiments [2]. As expected, the target strength is very weakly dep endent on the pulse length and sounder type, while the variation with c is more significant. The small temperature coefficient of c2 noted above is of little importance in comparison to that of c.

TABLE I

Theoretical target strengths of the 38.1mm tungsten carbide sphere in dB as a function of the sound velocity, pulse length and echosounder type. f is the centre frequency and BW is the nominal bandwidth. The calculations are based on the following parameter values:-

$c1=6853m/s$; $c2=4171m/s$; $\rho 1/\rho=14.508$

	Duich System f=38kHz; BW=4kHz			EK400 f=38kHz; BW=3kHz		
	Pulse length (ms)			Pulse length (ms)		
c (m/s)	0.5	1.0	3.0	0.5	1.0	3.0
1470	-42.19	-42.24	-42.26	-42.22	-42.24	-42.26
1490	-42.29	-42.34	-42.37	-42.33	-42.35	-42.37
1510	-42.32	-42.37	-42.40	-42.36	-42.38	-42.40

The range of sphere densities expected under normal manufacturing tolerances, about $\pm 0.5\%$, would have a negligible effect (less than 0.01dB) on the calculated sphere target strength at 38kHz [4].

Validity of the theoretical target strength

The accuracy of the calculated TS values described above depends upon the validity of the assumptions underlying the thoery, notably that the sphere is homogeneous and there is no external source of reflected energy contributing to the received signal. In practice, of course, the sphere has to be supported mechanically. The supporting material, which may have entrained microscopic quantities of air, could contribute some reflected energy which although small could be significant at the level of precision now being considered. Further, any living organisms or suspended solids in the water at the same range as the target would likewise contribute to the received signal and the practical error in a calibration. Some experimental verification of the theoretical target strength is therefore required, in particular to derive confidence limits on the TS values which would be applied in a calibration.

EXPERIMENTAL RESULTS

Present techniques for the direct measurement of absolute target strength fall short of the precision being claimed for the theoretical predictions. However, the theory may be tested by relative measurements, comparing one target with another. In particular, this type of experiment can provide information about the variability of the target strength.

Equipment and methods

Two series of experiments have been conducted in a West Scotland sea loch. The targets to be compared are suspended from the triangular frame of a motorised pan-tilt unit, as illustrated in Figure 2. The transducer (Simrad 38kHz ceramic) could be rotated relative to the frame around two axes and the transducer orientation is measured by angle encoders. The complete assembly is suspended at 20m depth below a moored raft.

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The targets are positioned nearly in line (within 1.5 degrees) and about 4m and 5.5m respectively below the transducer. This separation is just sufficient to resolve the reflections of a 1ms long pulse. The echo signals are processed by a fixed gain amplifier (time varied gain is not applied). The transducer is moved through a cycle of positions, to estimate the signal from each target on the acoustic axis. This cycle comprises nine positions about the first axis followed by nine positions about the second axis. The stationary axis is set to maximise the signal. For each position of the transducer, the echo energies are computed for 40 transmissions. The energy in this context is the integral of the square of the receiver output voltage. If the standard deviation of the echo energies is more than 1% of the corresponding mean, for either target, the 40 transmissions are repeated. This procedure eliminates much of the variability due to biological activity.

A quadratic regression curve is computed for each set of nine measurements, from which the maximum signal and the corresponding target direction are estimated for each target. Finally, the on-axis echo energy from each target is estimated by interpolation from the quadratic regression curves. This movement cycle lasts about six minutes and is repeated continuously under computer control. Thus the system produces about 10 target strength comparisons per hour, and each comparison is effectively an average measurement over 720 pings.

Calculation of the target strength difference

The target strength difference is TS=10Log (E1/E2), where E1 and E2 are the echo energies which would have been observed if the two targets had been insonified in the same position relative to the transducer. E1/E2 is derived from the measured echo energy ratio by applying corrections in respect of the target range difference, forward scatter by the upper target and the deviation from far field conditions. Further details of these corrections will be found in [3]. The most important is the range correction. The range from the transducer face to the target centre is estimated as $\frac{1}{2}c$ $(t-\Delta t)$ where t is the measured time delay between the start of the transmitter pulse and the half power point on the received echo waveform. Δt takes account of the delay contributed by the transducer and electronics. The sound velocity c is estimated from temperature and salinity measurements, using an empirical equation [8].

Results and discussion

The first series of experiments was conducted in 1981. The target strengths of brass, copper and tungsten carbide spheres were compared. The mean difference between the 60mm copper and 38.1mm tungsten carbide spheres was found to be 8.69$\pm$0.11dB (95% confidence limits, as are other limits quoted below), in good agreement with the value predicted by theory, 8.78dB [3]. This result supported the theoretical basis on which the absolute target strengths were calculated. However, significant differences up to 0.28dB were found between the five tungsten carbide spheres investigated, much more than would be expected from theory.

Subsequently, resonance experiments on the tungsten carbide spheres revealed that the target strength differences could not be explained by differences in the material density or sound velocities [4]. Variable reflectivity of the net bag which supported the sphere now appeared to be the most likely cause. The net bag was therefore redesigned to reduce the amount of material in it. Another innovation was the use of an ultrasonic cleaning bath to prepare the targets, for calibrations as well as these experiments, in addition to soaking them in soap solution, to reduce the risk of surface contamination.

In the 1984 series, 28 experiments were conducted, in each case comparing the TS of a different pair of targets from a stock of 12 tungsten carbide spheres. Each target was used in 4-6 different experiments. The target pairs were selected so that each sphere was in the upper and lower positions the same number of times. Thus the average TS difference is an estimate of the bias arising from inaccurate correction of the echo energy ratio. The 28 TS differences had a mean of 0.014dB and a standard deviation of 0.052dB. This suggests that any error in the analysis of the range and forward scatter corrections is very small, of the order of 0.01dB.

The variation of the results may arise from random effects or it may indicate real differences between the targets, or both. This has been investigated by an analysis of variance. The variance ratio is 3.38 which suggests systematic and highly significant (97.5% confidence level) differences between the targets.

A multiple regression was performed to obtain best estimates of the sphere target strengths relative to a common reference. Since there was no particular reason to use any one target more than another as the reference, this was taken as the average TS of all 12 targets. The results are shown in Table II.

TABLE II

Best estimates of the sphere target strengths relative to the mean target strength of all 12 spheres.

Sphere No.	Relative Target Strength (dB)
1	-0.01 ± 0.03
2	-0.01 ± 0.02
3	0.03 ± 0.03
4	-0.01 ± 0.03
5	-0.06 ± 0.03
6	-0.02 ± 0.03
7	0.04 ± 0.02
8	0.00 ± 0.03
9	0.00 ± 0.02
10	0.06 ± 0.02
11	0.05 ± 0.03
12	-0.08 ± 0.03

The estimated target strengths are spread over a 0.13dB range, again more than can be explained by the known variation of the sphere densities and sound velocities. However, the observed TS differences may be used to define confidence limits on the theoretical TS value, assuming that the latter is an accurate prediction of the average target strength of the spheres. As regards systematic differences between the targets, the limits are $\pm$ 0.09dB. They would apply to the long term average result from a calibration using a sphere selected at random.

There is in addition the calibration error due to the variation of the echo energy with time. This error will be less the longer is the duration of the calibration over which time the results are averaged. Figure 3 shows how the standard deviation of the mean TS difference depends upon the time over which the mean is computed, using the 1984 data. The time dependent variations are probably associated with scattering by objects in the water near the targets, such as fish or suspended solids. The worst effects of these unwanted scatterers are removed by the 1% limit on the standard deviation during the data collection, but a small residual cannot be avoided. However, in the two target rig, it may be supposed that the signal from each target will be independently subjected to interference. Thus the residual variance in our experiments should be twice that applying to a single target calibration.

The confidence limits on a calibration result averaged over an hour, a typical duration, ignoring the error contributed by systematic differences between targets, are estimated as ± 0.04dB. This value is consistent with the results reported by Simmonds et al [9]. The overall limits, including systematic errors and again relating to a one hour calibration run, are estimated as ± 0.10dB. Of course, this supposes that the calibration would be performed in waters where the biological activity and other environmental conditions are similar to those encountered in our experiments.

CONCLUSIONS

The reference target calibration technique has been shown to be capable of high accuracy. For the best results, reference spheres should be constructed from a material of known and consistent physical properties, and the sphere size should be chosen (a) to obtain the required target strength and (b) to ensure that the operating frequency is remote from any mechanical resonance of the sphere. The 38.1mm tungsten carbide sphere has been found to be a suitable target for the calibration of the 38kHz echosounders used in fishery research. The 95% confidence limits on the result from a one hour calibration run, taking account of errors in the assumed sphere target strength and the effect of spurious signals from the surrounding water, have been estimated as ±0.10dB. This is a considerable improvement on what was possible a few years ago.

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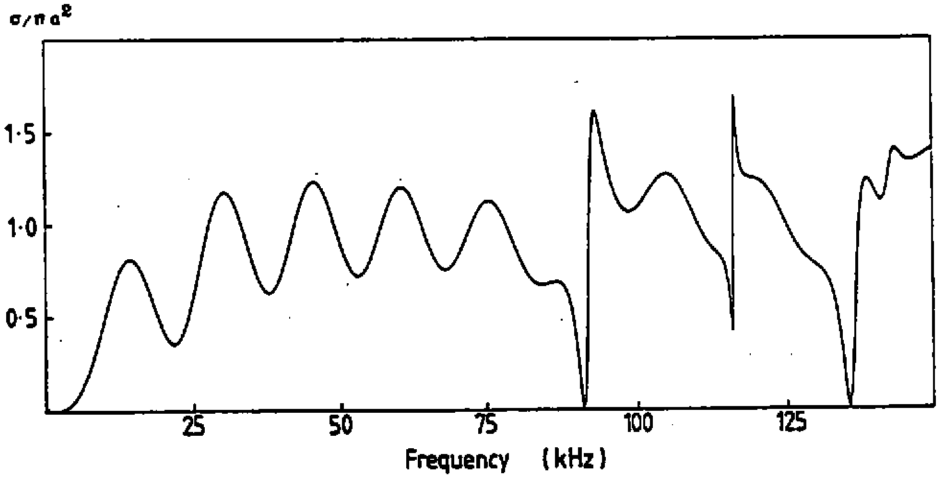

Figure 1. Frequency dependence of backscattering by the 38.1mm tungsten carbide sphere. The vertical axis is the ratio of the acoustic and geometric cross sections.

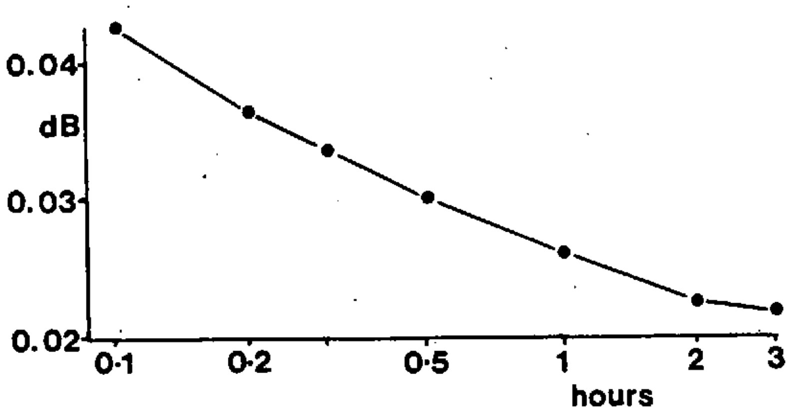

Figure 3. Standard deviation of the mean TS difference against the time over which the mean is computed.

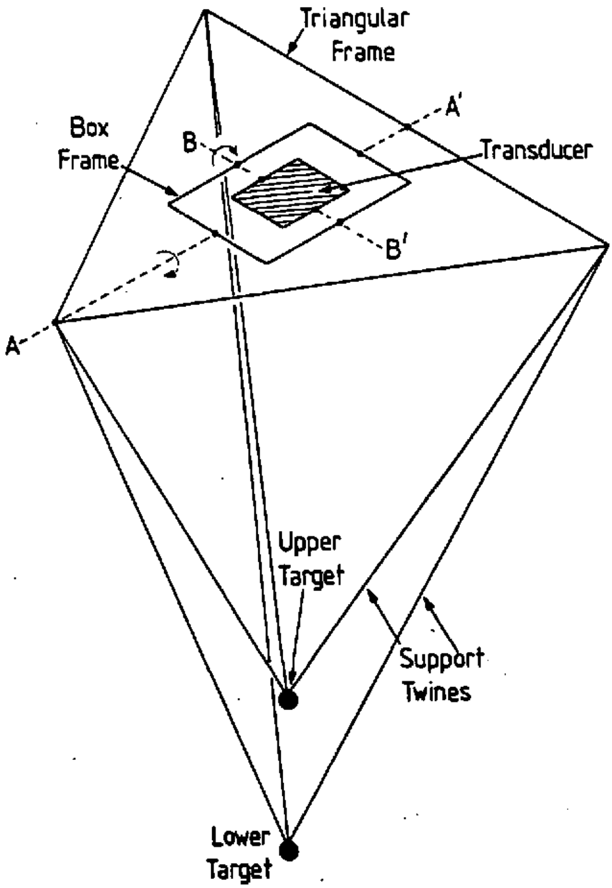

Figure 2. Experimental rig for the comparison of two targets. The transducer is rotated about the axes AA' and BB' to determine the signal maxima.