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# EFFECT OF MISSING MODES ON CALIBRATION SPHERE TARGET STRENGTHS

by

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## ABSTRACT

It has been suggested that modes of vibration of solid elastic spheres, such as those used in the calibration of echo sounder systems, can be affected by the manner of suspension. This hypothesis is investigated in the context of reported experimental calibration trials with the SIMRAD EK500/120-kHz echo sounder. In these, as many as four different spheres were used: 23- and 30.05-mm-diameter spheres composed of electrical grade copper and 33.2- and 38.1-mm-diameter spheres composed of tungsten carbide with 6% cobalt binder. Theoretical target strengths are computed for each sphere for the reported measurement conditions for a series of cases in which single vibration modes remain unexcited. The computed target strengths are compared with the corresponding experimental values. The working hypothesis is not supported by the data.

## INTRODUCTION

Some questions have been raised about the target strengths (TS) of standard spheres used for calibrating scientific echo sounders at 120 kHz. Measurements that may not be cited or quoted persuaded those who performed them that theoretically calculated target strengths were inaccurate. In particular, the TS of each of three spheres was found to be higher than the respective theoretical value by 1.5±0.1 dB, and that of the fourth sphere was also found to be higher but by 2.5 dB.

In discussing these remarkable findings, the matter of mode suppression arose. The argument was made that perhaps the manner of suspension of the target sphere affects the excitation of particular modes of vibration in the sphere. Since the process of echo formation depends on these modes, the value of target strength is similarly dependent. A change in mode composition will in general affect target strength.

The question of the effect of mode interruption or other suppression on target strength is interesting in its own right, without regard to the more serious matter of possible bias in target strength values determined *a priori* by theoretical computation. It is to investigate this question in the specific context of the anonymous measurement results that the present study is performed.

THEORY

According to the well-known theory for the scattering of planar acoustic waves by solid elastic spheres (Faran 1951, Hickling 1962, Gaunaurd and Überall 1983), the monochromatic backscattering amplitude in the farfield, f, can be written as an infinite sum of partial amplitudes $f_i$:

$$f = \sum_{i=0}^{\infty} f_i \quad . \qquad (1)$$

Convergence ensures that the infinite limit can be replaced by a finite number n. For example, in ordinary computations a conservative estimate of this limit is the largest integer less than or equal to $x + 6(x+1)^{\frac{1}{2}}$, where x=ka, k is the wavenumber, $k=2\pi/\lambda$ where $\lambda$ is the wavelength, and a is the sphere radius. The idealized monochromatic backscattering cross section $\sigma$ is defined simply as

$$\sigma = 4\pi|f|^2 \quad , \qquad (2)$$

and the target strength TS by

$$TS = 10 \log \frac{\sigma}{4\pi r_o^2} \quad , \qquad (3)$$

where $r_o$ is the reference distance of 1 m.

Because of the circumstances of measurement with instruments that transmit finite signals with bandwidth and that receive and process echo signals due to the same with physical filters that have finite bandwidth, the idealized definition of $\sigma$ is inadequate. The operational definition in common use in fisheries acoustics incorporates the transmit signal spectrum $S(\omega)$ and receiver frequency response function $H(\omega)$ along with the monochromatic farfield backscattering amplitude $F(\omega)=f$ through the following expression:

$$\sigma = 4\pi \int_0^{\infty} |SFH|^2 d\omega \Big/ \int_0^{\infty} |SH|^2 d\omega \quad , \qquad (4)$$

where $\omega$ is the angular frequency, $\omega=2\pi\nu$, and $\nu$ is the ordinary frequency in hertz (Foote 1982, MacLennan 1990). The target strength is defined as in equation (3).

In order to examine the effect of mode suppression on TS, the monochromatic backscattering amplitude F is computed in the standard way by a finite sum of modes but without individual single modes. In particular, the amplitude $F_{(p)}$ is computed, where mode p is suppressed. According to the usual finite version of equation (1), with $n=[ka + 6(ka+1)^{\frac{1}{2}}]$,

$$F_{(p)} = \sum_{\substack{i=0 \\ i\neq p}}^{n} F_i \quad . \qquad (5)$$

Alternatively, $F_{(p)}=F-F_p$. Use of $F_{(p)}$ for F in equation (4) allows computation of the mode-suppressed backscattering cross section $\sigma_{(p)}$, from which the mode-suppressed measure of target strength, $TS_{(p)}$, can be derived. Comparison with the corresponding reference measures $\sigma$ and TS enables the magnitude of effects to be gauged.

## NUMERICAL PARAMETERS

### Backscattering amplitude $F_i$

The mode or partial amplitude $F_i$ in equation (5) is computed according to the limiting expression in Goodman and Stern (1962), avoiding well-known typographical errors in Faran (1951) and Hickling (1962). This requires specification of the physical properties of the sphere, among other characteristics. For the two materials investigated here, electrical-grade copper, designated CU, and tungsten carbide with 6% cobalt binder, designated WC, the physical properties are the following:

| Material | Density ($kg/m^3$) | Sound speed (m/s) Longitudinal | Sound speed (m/s) Transverse |
|---|---|---|---|
| CU | 8947 | 4760 | 2288.5 |
| WC | 14900 | 6853 | 4171 |

Further ingredients in the computation of $F_i$ are the medium density $\rho$ and sound speed c, sphere radius a, and acoustic frequency $\nu$. Reference is made to the measurement parameters described in the anonymous work. For the freshwater experiment, the temperature was 17°C. The medium density has been assumed equal to 1000 $kg/m^3$ and the sound speed, 1473.2 m/s (Bart et al. 1964). For the seawater experiment, the salinity was nominally 34 ppt and the temperature range was 0.5-5.5°C. The medium density has been assumed equal to 1025 $kg/m^3$, and the sound speed, to lie in the nominal range 1450-1470 m/s.

Each of four spheres was used in the anonymous work. The diameters of the two copper spheres were 23 and 30.05 mm, notwithstanding statement of 30.5 mm for the larger diameter. The diameters of the tungsten carbide spheres were assumed to be 33.2 and 38.1 mm, although the diameter of 33.17 mm has also been mentioned in the literature. The corresponding names of the four spheres are CU23, CU30.05, WC33.2, and WC38.1.

Evaluation of $F_i$ is performed at each frequency over a finite band that is defined by the signal spectrum $S(\omega)$ and receiver frequency response function $H(\omega)$.

### Signal spectrum $S(\omega)$

The transmit signal in the transmitter is assumed to be an idealized square-wave modulated sinusoid,

$$s_o(t) = \mathrm{rect}\left(\frac{t-\tau/2}{\tau/2}\right) \sin \omega_o t \quad , \qquad (6)$$

where rect(y)=1 for $0 \leq y \leq 1$ and 0 otherwise, and $\omega_o$ is the resonant frequency, $\omega_o = 2\pi\nu_o$, $\nu_o = 119047$ Hz. The corresponding signal spectrum $S_o(\omega)$ is the Fourier transform of $s_o(t)$,

$$S_o(\omega) = \frac{\sin[(\omega-\omega_o)\tau/2]}{(\omega-\omega_o)\tau/2} \quad . \tag{7}$$

In passing through the transducer, which acts as a resonant filter, the spectral characteristics of the signal are transformed according to the factor,

$$|H_{tr}(\omega)| = \left[\frac{(\omega_o/2Q)^2}{(\omega-\omega_o)^2 + (\omega_o/2Q)^2}\right]^{\frac{1}{2}} \tag{8}$$

where the quality factor Q describes the sharpness of the resonant state. For the SIMRAD ES120/7 transducer, Q=9.

The spectrum of the transmitted signal in the water is thus

$$S(\omega) = S_o(\omega)H_{tr}(\omega) \quad . \tag{9}$$

Receiver frequency response function $H(\omega)$

The basis of this function for the EK500/120-kHz echo sounder is that measured by the manufacturer for the EK500/12-kHz receiver. The magnitude of $H_{12}(\omega)$ is shown in Fig. 1. The measurements were made without attachment of the transducer. The electronic part of the receiver frequency response function at 120 kHz is derived from that at 12 kHz by scaling,

$$H_{120}(10\omega) = H_{12}(\omega) \quad . \tag{10}$$

The acoustic signal in water is initially transformed under reception by the filtering action of the transducer. The frequency characteristic of this is identical to that under transmission, which is given by $H_{tr}(\omega)$ in equation (8). Thus the overall receiver frequency response function is given by a simple product,

$$H(\omega) = H_{tr}(\omega)H_{120}(\omega) \quad . \tag{11}$$

COMPUTATIONS AND RESULTS

Two sets of anonymous measurements are considered. The first concerns measurments of target strength performed in a freshwater tank at 17°C. These have been addressed through computations of target strength with single missing modes, $TS_{(p)}$, and comparison with the proper target strength, TS, for the respective calibration sphere. The difference $TS_{(p)}-TS$ is presented in Table 1 for each of the four spheres for a pulse duration of 0.3 ms.

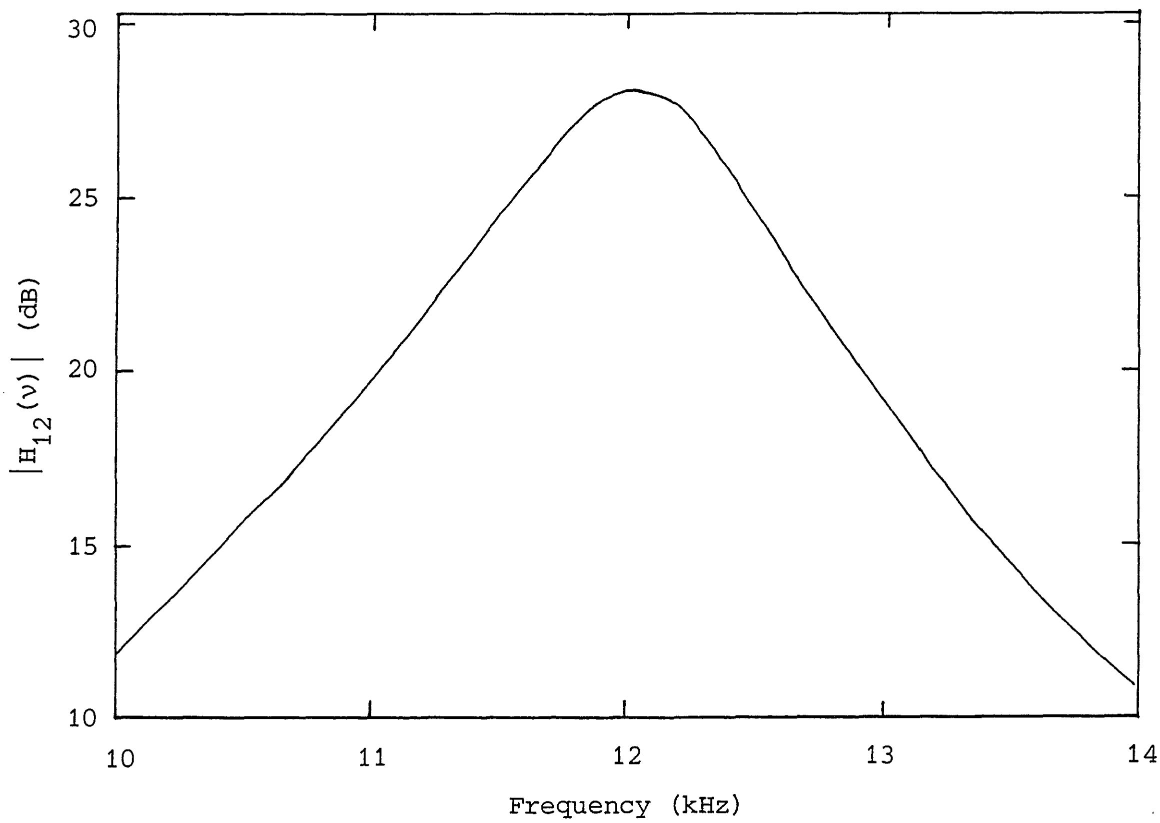


Fig. 1. Magnitude of the electronic part of the receiver frequency response function of the SIMRAD EK500/12-kHz echo sounder, measured without coupling of the transducer.

The second set of anonymous measurements that are considered concern variations in system gain due to changes in seawater temperature over the range 0.5-5.5°C and changes in pulse duration from 0.1 to 0.3 ms. As in the first case, the quantity $TS_{(p)}$-TS is computed. In all but two cases, the variation in this quantity over the quoted temperature range, as represented by the corresponding nominal sound speed range 1450-1470 m/s, is monotonic. In the two dissenting cases, the discrepancy is only 0.01 dB. The results for the variation in temperature are presented in Table 2, assuming the pulse duration 0.3 ms. Results for the variation with pulse duration are presented in Table 3, assuming the mean temperature of the interval, with nominal sound speed 1460 m/s.

## DISCUSSION

The results in Tables 1-3 are to be viewed in the context of the anonymous observations. In the case of the freshwater measurements at 17°C, the reported discrepancies between measurement and theoretical expectation were 1.5 dB for CU23, 1.4 dB for CU30.05, 2.5 dB for WC33.2, and 1.6 dB for WC38.1. If single missing modes of vibration are to explain these, then the nearest reasonable candidate cases are p=7 for CU23 with $\Delta TS=TS_{(p)}-TS=1.36$ dB, p=6 for CU30.05 with $\Delta TS=1.89$ dB,

Table 1. Difference in TS of four spheres for calibrating the SIMRAD EK500/120-kHz echo sounder relative to the respective, tabulated reference value in the absence of vibration mode p. The pulse duration is 0.3 ms. The medium is freshwater at 17°C.

| p | CU23 | CU30.05 | WC33.2 | WC38.1 |
|---|---|---|---|---|
| 0 | -1.40 | 0.15 | -0.91 | 0.56 |
| 1 | 0.09 | -2.75 | 2.10 | -3.04 |
| 2 | -16.98 | -0.38 | -12.19 | 1.24 |
| 3 | 0.14 | -7.14 | 0.12 | -9.78 |
| 4 | 0.02 | 0.13 | 0.29 | -1.19 |
| 5 | 4.37 | 2.11 | 9.42 | 5.56 |
| 6 | -1.72 | 1.89 | -0.06 | 9.85 |
| 7 | 1.36 | -7.26 | 1.52 | -9.27 |
| 8 | -0.18 | 4.25 | 3.44 | -2.26 |
| 9 | 0.03 | -1.54 | 3.45 | 6.15 |
| 10 | 0 | 0.34 | 0.67 | 0.77 |
| 11 | | -0.06 | -0.05 | 3.08 |
| 12 | | 0.01 | 0.02 | -0.97 |
| 13 | | 0 | 0 | 0.21 |
| 14 | | | | -0.04 |
| 15 | | | | 0.01 |
| 16 | | | | 0 |
| TS | -40.39 | -36.62 | -40.61 | -39.55 |

p=1 for WC33.2 with ΔTS=2.10 dB, and p=2 for WC38.1 with ΔTS=1.24 dB. If the precise means of suspension of the four spheres were different and single missing modes were responsible, then the identified modes could provide an explanation to within 0.1, 0.5, 0.4, and 0.4 dB, respectively. The tolerances of the experimental results are unspecified, but an accuracy of ±0.1 dB is not inconceivable under circumstances in which a charge of inaccuracy in established TS-values is made. If the tolerances are ±0.1 dB, then the agreement, assuming arbitrary single missing modes, is poor. If, however, the precise means of suspension were identical and single missing modes were responsible, then the same missing mode would be responsible. This requirement is stringent: inspection of Table 1 discloses no candidate single mode, owing to magnitudes or signs of the TS differences.

In examining the second experiment, it is sufficient to consider only two spheres, CU30.05 and WC33.2. As noted earlier, the first sphere was described in the anonymous work as having a diameter of 30.5 mm, but it is assumed that this is a typographical error. The observations revolve around the so-called target strength gain $G_{TS}$ and volume backscattering strength gain $G_{Sv}$, which are internal, independently adjustable operating parameters of the EK500 echo sounder. What is to be examined here is the consistency of the anonymous observations in regard to the missing-modes analysis in Tables 2 and 3.

The first anonymous observation was that $G_{TS}$ and $G_{Sv}$ were considerably higher for the shorter pulse duration and at the higher temperatures. From the reference values for TS in Table 3, it is seen that the TS is lower for each of the two spheres at the shorter pulse duration, although the magnitude is 0.35 dB for CU30.05 and 0.03 dB for WC33.2. With increasing temperature, hence sound speed, it is seen from Table 2 that the TS is higher for each sphere, increasing by 0.42 dB for CU30.05 and 0.18 dB for WC33.2. Thus the two tendencies or dependences oppose each other. Only in the case of the shorter pulse duration, with decreasing TS, hence increasing gains, does the sign of the change agree, but the magnitude, corresponding to a change in $G_{TS}$ and $G_{Sv}$ of about 0.02 dB for WC33.2 is far less than the observed or claimed 0.2-0.5 dB. For CU30.05, the discrepancies are larger.

The second observation was that the two gain factors determined with the 33.2-mm-diameter WC sphere were 1.5 and 1.0 dB greater than the respective gain factors determined with the 30.05-mm Cu sphere. In this case, reference must be made to the difference in TS with changing vibration mode p. The mentioned increase in gain would correspond to a decreased TS by 2.3 dB. If this were due to the same single missing mode, a case should be found in Table 3 that supports this. In the closest case, p=8, the change is a decrease of about 1.9 dB at 0.3 ms and 1.6 dB at 0.1 ms.

It is to be noted, perhaps, that the present computations of target strength are based on an operational definition of target strength that pertains to echo integrator calibration, whereas an amplitude was measured in the anonymous work. The difference should not be significant given the use of targets at non-resonant frequencies, as well as the use of targets which are optimal in at least two cases, those of CU23 and WC33.2.

An omission so far in this study has been a consideration of whether modes can be suppressed and under what circumstances this might occur. Clearly, some suspensions will not hinder the excitation of particular modes, while other suspensions almost certainly will suppress or interrupt modes. An illustration is provided by a copper sphere that is suspended by a single loop

Table 2. Differences in TS of four spheres for calibrating the SIMRAD EK500/120-kHz echo sounder relative to the respective, tabulated reference value in the absence of vibration mode p. The pulse duration is 0.3 ms. Differences are shown for each of two sound speeds, representing the nominal limits for the temperature range 0.5-5.5°C and sea water of salinity 34 ppt. The dependences are monotonic except for the sphere WC38.1 at p=11 and 13, for which the deviation is 0.01 dB.

| | CU23 | | CU30.05 | | WC33.2 | | WC38.1 | |
|---|---|---|---|---|---|---|---|---|
| P | 1450 | 1470 | 1450 | 1470 | 1450 | 1470 | 1450 | 1470 |
| 0 | -1.30 | -1.40 | 0.05 | 0.14 | -0.93 | -0.91 | 0.66 | 0.57 |
| 1 | -0.10 | 0.06 | -2.37 | -2.75 | 1.92 | 2.07 | -3.79 | -3.15 |
| 2 | -15.14 | -16.78 | -0.75 | -0.39 | -9.17 | -11.82 | 1.37 | 1.24 |
| 3 | 0.00 | 0.10 | -6.41 | -7.03 | 0.01 | 0.11 | -11.30 | -10.09 |
| 4 | 0.40 | 0.04 | -0.23 | 0.06 | -1.27 | 0.06 | 0.12 | -1.00 |
| 5 | 4.35 | 4.37 | 3.13 | 2.21 | 9.63 | 9.44 | 4.46 | 5.41 |
| 6 | -3.40 | -1.83 | 1.51 | 1.86 | 1.73 | 0.16 | 10.31 | 9.90 |
| 7 | 1.88 | 1.41 | -11.42 | -7.62 | 1.47 | 1.52 | -3.71 | -8.48 |
| 8 | -0.32 | -0.19 | 4.96 | 4.36 | 2.15 | 3.27 | -0.92 | -2.05 |
| 9 | 0.05 | 0.03 | -2.57 | -1.64 | 4.84 | 3.65 | 5.28 | 6.05 |
| 10 | -0.01 | 0 | 0.54 | 0.36 | 0.13 | 0.61 | 3.26 | 1.12 |
| 11 | 0 | | -0.10 | -0.06 | 0.16 | -0.03 | 3.06 | 3.09 |
| 12 | | | 0.01 | 0.01 | -0.02 | 0.01 | -0.80 | -0.96 |
| 13 | | | 0 | 0 | 0 | 0 | 0.21 | 0.21 |
| 14 | | | | | | | -0.04 | -0.04 |
| 15 | | | | | | | 0.01 | 0.01 |
| 16 | | | | | | | 0 | 0 |
| TS | -40.31 | -40.37 | -37.11 | -36.69 | -40.79 | -40.61 | -39.80 | -39.56 |

Table 3. Differences in TS of four spheres for calibrating the SIMRAD EK500/120-kHz echo sounder relative to the respective, tabulated reference value in the absence of vibration mode p for each of two pulse durations, 0.1 and 0.3 ms, at the medium sound speed 1460 m/s.

| | CU23 | | CU30.05 | | WC33.2 | | WC38.1 | |
|---|---|---|---|---|---|---|---|---|
| p | 0.1 | 0.3 | 0.1 | 0.3 | 0.1 | 0.3 | 0.1 | 0.3 |
| 0 | -1.33 | -1.35 | 0.14 | 0.10 | -0.89 | -0.92 | 0.61 | 0.61 |
| 1 | 0.08 | -0.01 | -2.45 | -2.58 | 2.04 | 2.00 | -3.25 | -3.48 |
| 2 | -11.78 | -16.23 | -0.39 | -0.55 | -10.41 | -10.48 | 1.34 | 1.31 |
| 3 | 0.22 | 0.05 | -6.88 | -6.79 | 0.08 | 0.07 | -10.05 | -10.86 |
| 4 | 0.06 | 0.20 | 0.42 | -0.06 | -0.12 | -0.59 | -0.62 | -0.41 |
| 5 | 4.44 | 4.37 | 2.59 | 2.66 | 9.49 | 9.53 | 5.13 | 4.96 |
| 6 | -2.12 | -2.57 | 1.94 | 1.71 | 0.90 | 0.92 | 9.99 | 10.10 |
| 7 | 1.57 | 1.64 | -8.23 | -9.37 | 1.46 | 1.52 | -5.18 | -5.96 |
| 8 | -0.22 | -0.25 | 4.67 | 4.67 | 3.06 | 2.74 | -1.70 | -1.44 |
| 9 | 0.04 | 0.04 | -1.87 | -2.07 | 4.06 | 4.25 | 5.80 | 5.69 |
| 10 | 0 | 0 | 0.41 | 0.44 | 0.42 | 0.40 | 2.02 | 2.23 |
| 11 | | | -0.07 | -0.08 | 0.05 | 0.05 | 2.98 | 3.10 |
| 12 | | | 0.01 | 0.01 | 0 | 0 | -0.82 | -0.91 |
| 13 | | | 0 | 0 | | | 0.20 | 0.22 |
| 14 | | | | | | | -0.03 | -0.04 |
| 15 | | | | | | | 0.01 | 0.01 |
| 16 | | | | | | | 0 | 0 |
| TS | -40.54 | -40.34 | -37.25 | -36.90 | -40.71 | -40.68 | -39.64 | -39.66 |

of monofilament nylon with ends attached to the sphere by an epoxy weld in a shallow bore. If the sphere were ensonified from the side, with vertical alignment of the bore, then even-numbered modes, with antinodes in the equatorial plane containing the bore, would generally be affected. Identifying the particular modes and guessing at their proportionate contributions could be an interesting academic exercise, especially if reliable published data were available. A more fruitful, radically different approach, were it necessary to pursue the matter further, could be undertaken through a deterministic computation with the finite-element boundary-element method (Francis 1993).

At present, only single missing modes have been quantitatively investigated. The primary if anonymous observation of similar, large discrepancies in the target strengths of four standard spheres has seemed too glaring to require or justify a random walk into the maze of missing multiple or partially suppressed modes.

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