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CALIBRATION REFLECTOR

by

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ABSTRACT

Calibration of scientific echo sounders and integrators entails, inter alia, measurement of the dynamic range. This can be done by repeating on-axis measurements of echoes from each of two different standard targets. When a large dynamic range is to be tested, use of a reflector may be convenient. An example is given for which a target strength of roughly 15 dB was desired for use at 38 kHz. The solution: a 12-mm-thick copper disk of 50-cm diameter, is described. Results from its first field applications, where linear operation of a new acoustic system over a 56-dB range was established, are given.

RESUME: REFLECTEUR D'ETALONNAGE

L'étalonnage d'écho-sondeurs et d'intégrateurs scientifiques entraîne, parmi autres choses, la mesure de la gamme dynamique. Ceci peut être réalisé par des mesures axées répétées des échos provenant de deux cibles standard. Dans le cas d'une gamme dynamique très large, l'utilisation d'un réflecteur peut être convenable. Dans l'exemple donne ci-dessous, un index de réflexion de 15 dB était souhaitable pour une fréquence de 38 kHz. La solution consiste dans l'utilisation d'un disque en cuivre de 50 cm de diamètre. On présente les résultats de sa première utilisations sur le terrain, où l'opération linéaire d'un nouveau système acoustique d'une gamme de 56 dB était établie.

INTRODUCTION

The dynamic range of the new SIMRAD EK500 scientific echo sounder is claimed to be 160 dB (Bodholt et al. 1988, 1989). While the manufacturer may feel no compunction to verify this by measurement, it behooves the user, especially the first, to test the system as rigorously as possible.

Application of the echo sounder in fisheries surveying defines the most important part of the dynamic range. This is that spanned by echoes from commercially important fish to echoes from hard flat bottoms.

Experience has shown that the performance of scientific echo sounders and echo integrators is linear over a wide range of fish echoes (Bayona 1984). Invariably, however, bottom echoes, and weaker echoes too, have caused saturation in the receiver. Thus, apropos of the new EK500, it is important that the performance at the upper end of the dynamic range be verified.

A particular motivation for examining the response of the echo sounder to powerful echoes is the desire, if not need, to process bottom echoes. Such processing may (1) aid bottom detection through sharper delineation of the bottom, and (2) improve discrimination of demersal fish echoes from the bottom echo. In addition, promising new schemes of bottom identification (Orlowski 1984,1989, Burns et al. 1989) might also be incorporated in these tasks if receiver saturation is avoided.

The requirement for a very strong test scatterer is thus established. Historically, in sonar, this need has been addressed by the triplane (Bergmann 1946), loaned from optical signaling. Use of this as a precise measurement target is complicated by the difficulty of determining the target strength a priori (Hamada 1976).

Another powerful test scatterer is the focused liquid-filled spherical reflector (Folds 1971). The reported agreement of experimental data with theoretical computations is excellent for some liquids and frequencies, and relatively poor, for calibration use, for others. Another disadvantage of the focusing system for the present application, which it shares with the triplane, is its composite nature.

At least two other apparently powerful targets are described in patents. One is a stack of onionskin sheets wrapped in aluminium and hermetically sealed with neoprene (Bulmer and Parssinen 1979). The dominant source of echoes is air trapped in the paper stack. The other target consists of bubbles of oxygen and hydrogen which are produced by electrolysis of sea water in saturated foam and held in the porous electrodes (Cluzel et al. 1980). The target strengths of these targets are generally unknown; neither measurement nor computation is likely to determine the target strength to the necessary degree of accuracy for calibration.

A derivative of the triplane target for echo sounder calibration is the circular disk. In the following, this is modelled, and an approximate expression is presented for the farfield backscattering amplitude for oblique incidence. A particular design, consisting of material, diameter and thickness, is specified. Application of the disk in verifying part of the dynamic range of the new echo sounder is described.

MODEL

Sound scattering by a circular disk has been modelled in a number of ways. These fall into two general categories, as the disk is assumed to be vanishingly thin or of finite thickness.

Models of disks of vanishing thickness have assumed ideal boundary conditions for the field on the disk. Sleator (1969) has given exact solutions for scattering of monochromatic spherical and plane waves by hard and soft disks. The solutions are expressed in terms of oblate spheroidal functions. The special case of scattering by normally incident plane waves has been studied by Leitner (1949). Numerical results for the angular dependence of the farfield scattering amplitude have been obtained from both the exact solution and the Kirchhoff approximation. These show increasing agreement with increasing value of the product of the wavenumber k and radius a, which is quite good out to 30 deg already for ka=5. The special case of backscattering of obliquely incident plane waves has been studied by Hamada (1976). Good agreement is obtained between the Kirchhoff approximation and empirical data for an immersed 120-mm-diam disk at 50 kHz, that is, with ka≐12.6.

Disks of finite thickness have been modelled by means of the finite-element method. Hunt et al. (1975) compute the scattered field in the nearfield of a circular disk for normal incidence. Knittel et al. (1975) do the same for oblique incidence.

In order to compute the target strength of a rather large, circular, elastic disk of finite thickness, a composite model is used. In this, the geometric and elastic or physical parts are separated. The geometric effect of the disk, as described by Hamada (1976), as well as by Urick (1975) and others, is contained in this expression for the farfield backscattering amplitude for a plane wave incident on the disk at the angle θ with respect to the normal:

$$|f_{b,geom}| = \frac{\pi a^2}{\lambda} \left| \cos\theta \, \frac{J_1(2ka\sin\theta)}{ka\sin\theta} \right| \quad , \tag{1}$$

where a is the disk radius, $k=2\pi/\lambda$ is the wavenumber, and λ is the acoustic wavelength. The expression is consistent with that of Leitner (1949), although for scattering of a normally incident plane wave.

The effect of the elasticity and finite thickness of the disk is represented by the amplitude coefficient B for reflection of a plane wave by an immersed infinite plate of thickness d. The physical properties of the immersion medium are described by the medium density ρ and sound speed c. The physical properties of the plate are described by its density ρ_1 and longitudinal and transverse wave sound speeds, c_1 and c_2, respectively. The coefficient is determined in the manner of Kolsky (1963). Here there are six unknowns: the amplitudes of reflected and transmitted waves in the immersion medium, and the amplitudes of internal longitudinal and transverse waves propagating both forwards and backwards in the elastic plate. These are determined by simultaneous solution of the six equations arising from the boundary conditions, namely continuity of normal component of velocity, continuity of normal component of stress, and vanishing of tangential stress, which apply at each face or side of the plate. The result for the reflection coefficient is

$$B = \frac{U - V}{U + V - 2iW} \quad , \tag{2}$$

where $U = u^2[(u_1^4+u_2^4)\sin\kappa_1 \sin\kappa_2 + 2u_1^2u_2^2(1-\cos\kappa_1 \cos\kappa_2)]$,

$V = (\rho/\rho_1)^2 u_3^6 \sin\kappa_1 \sin\kappa_2$,

$W = (\rho/\rho_1) u u_3^3 (u_1^2 \cos\kappa_1 \sin\kappa_2 + u_2^2 \sin\kappa_1 \cos\kappa_2)$,

$u = \kappa \cos\theta$,

$u_1 = \kappa_2 \cos 2\theta_2$,

$u_2 = \kappa_1 (\sin 2\theta_1 \sin 2\theta_2)^{1/2}$,

$u_3 = (\kappa_1 \kappa_2^2 \cos\theta_1)^{1/3}$,

$\kappa = kd$,

$\kappa_1 = k_1 d$,

$\kappa_2 = k_2 d$,

and k, k_1 and k_2 are the wavenumbers of pressure wave in the immersion medium and longitudinal and transverse waves in the elastic plate, respectively. The several angles θ, θ_1 and θ_2 are connected by Snell's Law, namely $k \sin\theta = k_1 \sin\theta_1 = k_2 \sin\theta_2$. The expression for B is applicable for $\theta < \arcsin(c/c_1)$, i.e., for incident angles less than the first critical angle, for longitudinal waves. At and beyond this angle, the analysis is known to be complicated (Kolsky 1963).

For present purposes, the case of normal incidence, $\theta = 0$, is of greatest interest. At this angle, $B = B_o$, where

$$B_o = \frac{(z_1^2 - z^2)\sin\kappa_1}{(z_1^2 + z^2)\sin\kappa_1 - 2izz_1 \cos\kappa_1} \quad , \tag{3}$$

where $z = \rho c$, $z_1 = \rho_1 c_1$. This expression is equivalent with that in Eq. 6.12 in Kinsler et al. (1980) for a homogeneous immersion medium.

In any case, the composite backscattering amplitude for oblique incidence at the angle θ is

$$|f_b| = |Bf_{b,geom}| \quad , \tag{4}$$

and the backscattering cross section is

$$\sigma = 4\pi |f_b|^2 \quad . \tag{5}$$

By definition, the target strength is

$$TS = 10 \log \frac{\sigma}{4\pi} \quad , \tag{6}$$

hence,

$$TS = 10 \log |f_b|^2 \quad . \tag{7}$$

The target strength of an idealized perfectly reflecting sphere of 2-m radius is 0 dB.

For normal incidence, $|f_{b,geom}| = \pi a^2/\lambda$, hence $TS = 10 \log (B_o \pi a^2/\lambda)^2$.

COMPUTATIONAL RESULTS

Electrical-grade copper is the preferred material, for many of the reasons given by Foote (1982). The properties of copper are assumed to be $\rho_1 = 8947$ kg/m^3, $c_1 = 4760$ m/s, and $c_2 = 2288.5$ m/s. The properties of the immersion medium, sea water, are represented by $\rho = 1025$ kg/m^3 and $c =$ 1470 m/s.

Clearly, from Eq. (2), B is very close to unity for $\theta < \arcsin (c/c_1)$. In fact, $B \doteq 0.99$ for $\theta \lesssim 18$ deg and $10 \log B^2 \doteq -0.07$ dB for $\theta \lesssim 9$ deg. For normal incidence,

$$TS = 10 \log (\pi a^2/\lambda)^2 - 0.07 \quad . \tag{8}$$

This expression has been evaluated for 12-mm-thick copper disks of diameters 5, 10, 15, 30 and 50 cm for ensonification by a continuous plane wave at 38 kHz. The results are presented in Table 1.

Table 1. Theoretical target strengths of five 12-mm-thick copper disks at 38 kHz when immersed in sea water at 5°C.

Diameter 2a(cm)	ka	(cm^2)	$10 \log \|f_{b,geom}\|^2$	TS(dB)
5	4.1	0.0324	-25.9	-26.0
10	8.1	0.518	-13.8	-13.9
15	12.2	2.62	-6.8	-6.9
30	24.4	42.0	5.2	5.2
50	40.6	324	14.1	14.0

APPLICATION

On the basis of these results, a set of disks was cut from a 1-m^2 plate of 12-mm-thick electrical-grade copper. Six equally spaced holes of c. 1.5-mm diameter were drilled in each disk about 5 mm from the perimeter. Countersinking was performed at each hole to reduce line stress at the edges. Lines of monofilament nylon running through each of three equidistant holes were knotted on the underside and brought together in a common knot. This was about 2 m from the 50-cm-diameter disk. Thus each disk could be suspended from a single point, and otherwise measured as a standard target (Foote et al. 1987).

Measurements were made on some of the disks during the first trials of the new SIMRAD EK500 echo sounder and the new Bergen Echo Integrator. These were held on board R/V G. O. SARS 5-15 December 1988 and 6-10 March 1989.

Collateral measurements were made on standard spheres according to the standard standard-target procedure (Foote et al. 1987). Two of the target spheres were the 60-mm-diam Cu sphere (Foote 1982) and 38.1-mm-diam ball bearing made from tungsten carbide with 6% Co binder (MacLennan 1982).

Because of the newness of the echo sounder, which was in a preliminary, pre-prototype state, adjustments were made to the instrument by the manufacturer's representatives during both cruises. Constancy in the echo sounder settings was therefore a condition for data selection. This was the case for each of the two pairs of measurements shown in Table 2, although made with different split-beam transducers. The pulse duration was 1.0 ms, the center frequency 38 kHz, and receiver bandwidth 3.8 kHz.

Table 2. Target strengths, in decibels, of several targets used during two trials of the new SIMRAD EK500 echo sounder. $\hat{TS}$ denotes the measured value, TS_{th} the theoretical, and expected, value, and $\hat{TS}_{corr}$ the corrected empirical value based on the 60-mm-diam Cu sphere.

Cruise period	Calibration object	$\hat{TS}$	TS_{th}	$\hat{TS}_{corr}$
December 1988	Cu sphere, 60-mm diam	-33.2	-33.5	-33.5
December 1988	WC sphere, 38.1-mm diam	-41.9	-42.3	-42.2
March 1989	Cu sphere, 60-mm diam	-33.3	-33.6	-33.6
March 1989	Cu disk, 50-cm diam	14.5	14.0	14.2

Each measurement represents the maximum value of target strength as derived by the split-beam function incorporated in the echo sounder. The examined data were those printed during the respective calibration exercises. Data collected on the same targets but with other echo sounder settings were similar to these, the rather small differences being due to then-uncompensated differences in filtering.

The theoretical values shown in Table 2 were derived in the usual manner, hence respected measurements of hydrography at the particular calibration sites. This accounts for the 0.1-dB difference in values of TS_{th} for the 60-mm-diam Cu sphere between the two trials.

In correcting or adjusting the measured target strength values $\hat{TS}$, the 60-mm-diam Cu sphere was assumed to be the reference.

DISCUSSION

The so-called target strength window or function of the new SIMRAD EK500 echo sounder presents the angular position data together with each target strength datum. This is of considerable help in the important centering operation. For the calibration sphere, the position with maximum echo amplitude was essentially on axis. For the 50-cm-diam disk, however, the maximum was obtained nearly 2 deg off axis, which indicates a misalignment of the acoustic axes of transducer and disk. This is understandable in view of the extreme directionality of scattering by the disk, with ka=40.6, hence two-way half-beamwidth of 1.1 deg. Since the transducer was stabilized, the disk must have been somewhat askew during its measurement.

This same skewness of alignment, which accounts for the off-transducer-axis maximum in target strength, also renders the target strength measurement subject to errors in beam pattern compensation (MacLennan and Svellingen 1986). Preliminary measurements show no large near-axis error, but a careful mapping of the beam pattern with standard-target sphere, as by Simmonds (1984) or Reynisson (1985), is needed.

All in all, the measurement of the large copper disk seems reasonable. Certainly the agreement between theoretical expectation and measurement is excellent for each of the calibration objects shown in Table 2. This was expected for the spheres, as similar agreement has been obtained during previous calibration trials without exception. Given the manufacturer's boast of a dynamic range of 160 dB and no evidence of receiver saturation at any time during the two trial cruises and during more recent field uses of the new echo sounder, a 14-dB target should not cause saturation.

Thus, the linearity of operation of the new echo sounder may be said to have been established over the range from -42 to 14 dB, or 56 dB *in toto*.

Measurements with the echo integrator function of the EK500 echo sounder show the same linearity for the standard target spheres. Because of the extreme sensitivity of echo level from the large disk to small movements, such as uncontrolled swaying due to surface motions and underwater currrents while at anchor during calibration exercises, the average value of target strength is considerably less than the reported maximum value. The echo integrator value reflects this variable registration.

If the dynamic range of the echo sounder can be assumed to be what the manufacturer claims, then the measurement justifies use of the elastic-disk backscattering model, at least on axis. The large wavenumber-radius product ka argues strongly for the principal dependence of backscattering on the angle of incidence stated in Eq. (2). There is both theoretical and empirical evidence for the validity of the Kirchhoff approximation, which seems to receive further practical support here.

Investigation of the second angular scattering factor, in Eq. (3), requires, at least from initial appearances, special measurement conditions. Because of the relative largeness of the first critical angle, $\theta = \arcsin(c/c_1) \doteq 18$ deg, the matter need not be pursued in the present context.

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REFERENCES

Bayona, J. D. R. 1984. Comparison of acoustic survey systems for use in developing countries. FAO Fish. Circ., 778: 1-20.

Bergmann, P. G. 1946. Experimental procedures. In Physics of Sound in the Sea, Summary Technical Report of Division 6, NDRC, Vol. 8. Reprinted by Department of the Navy, Washington, D.C. (1969). 566 pp.

Bodholt, H., Nes, H., and Solli, H. 1988. A new echo sounder system for fish abundance estimation and fishery research. ICES C.M. 1988/B:11. 6 pp.

Bodholt, H., Nes, H., and Solli, H. 1989. A new echo-sounder system. Proc. I.O.A., 11(3): 123-130.

Bulmer, R. J., and Parssinen, E. J. 1979. Underwater acoustic pressure release reflector. J. acoust. Soc. Am., 65: 556.

Burns, D. R., Queen, C. B., Sisk, H., Mullarkey, W., and Chivers, R. C. 1989. Rapid and convenient acoustic sea-bed discrimination for fisheries applications. Proc. I.O.A., 11(3): 169-178.

Cluzel, P. H., Quivy, M. G., and Tocquet, B. 1980. Underwater acoustic reflectors. J. acoust. Soc. Am., 68: 1910-1911.

Folds, D. L. 1971. Target strength of focused liquid-filled spherical reflectors. J. acoust. Soc. Am., 49: 1596-1599.

Foote, K. G. 1982. Optimizing copper spheres for precision calibration of hydroacoustic equipment. J. acoust. Soc. Am., 71: 742-747.

Foote, K. G., Knudsen, H. P., Vestnes, G., MacLennan, D. N., and Simmonds, E. J. 1987. Calibration of acoustic instruments for fish density estimation: a practical guide. ICES Coop. Res. Rep., 144. 69 pp.

Hamada, E. 1976. Study on the ultrasonic corner reflector for fish finder. II. Computation of the target strength about a corner reflector. J. Tokyo Univ. Fish., 63: 41-52.

Hunt, J. T, Knittel, M. R., Nichols, C. S., and Barach, D. 1975. Finite-element approach to acoustic scattering from elastic structures. J. acoust. Soc. Am., 57: 287-299.

Kinsler, L. E., Frey, A. R., Coppens, A. B., and Sanders, J. V. 1980. Fundamentals of acoustics. Third edition, Wiley, New York. 480 pp.

Knittel, M. R., Nichols, C. S., and Barach, D. 1975. Scattering of obliquely incident plane acoustic waves by an elastic disk. J. acoust. Soc. Am., 58: 983-995.

Kolsky, H. 1963. Stress waves in solids. Dover, New York. 213 pp.

Leitner, A. 1949. Diffraction of sound by a circular disk. J. acoust. Soc. Am., 21: 331-334.

MacLennan, D. N. 1982. Target strength measurements on metal spheres. Scot. Fish. Res. Rep., 25. 11 pp.

MacLennan, D. N., and Svellingen, I. 1986. Simple calibration of a split-beam echo-sounder. ICES C.M. 1986/B:8. 6 pp.

Orlowski, A. 1984. Application of multiple echoes energy measurements for evaluation of sea bottom type. Oceanologia, 19: 61-78.

Orlowski, A. 1989. Application of acoustic methods to correlation of fish density distribution and the type of sea bottom. Proc. I.O.A., 11(3): 179-185.

Reynisson, P. 1985. A method for measuring the equivalent beam angle of hull mounted transducers. ICES C.M. 1985/B:4. 13 pp.

Simmonds, E. J. 1984. A comparison between measured and theoretical equivalent beam angles for seven similar transducers. J. Sound Vib., 97: 117-128.

Sleator, F. B. 1969. The disc. In Electromagnetic and Acoustic Scattering by Simple Shapes, pp. 528-588, Ed. by J. J. Bowman, T. B. A. Senior, and P. L. E. Uslenghi. North-Holland, Amsterdam. 728 pp.

Urick, R. J. 1975. Principles of underwater sound. Second edition, McGraw-Hill, New York. 384 pp.