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THREE-IN-ONE TRANSDUCER DESIGN FOR A TRIPLE-FREQUENCY ECHO SOUNDER

by

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ABSTRACT

A design is outlined in which three different kinds of transducer elements are arranged concentrically and in near proximity. It will be possible to drive the elements simultaneously, thus forming three coaxial beams at distinct frequencies. Under good signal-to-noise conditions, the acoustically sampled volume will be similar for each of the beams.

RESUME: MISE AU POINT D'UN TRANSDUCTEUR TRIPLE POUR UN SONDEUR "TRIFREQUENCE"

Cette communication décrit une esquisse de transducteur, composé de 3 différents types d'éléments, assemblés concentriquement et très proches les uns des autres. Il sera possible d'exciter les éléments simultanément et l'on obtient ainsi 3 faisceaux concentriques à des fréquences distinctes. En présence de bonnes conditions signal à bruit, le volume échantillonné acoustiquement sera similaire pour chacun des faisceaux.

INTRODUCTION

The new SIMRAD EK500 scientific echo sounder (Bodholt et al. 1988, 1989) can operate simultaneously as many as three different transducers. Each of these may be either single-beam or split-beam. It is expected that the use of multiple frequencies in acoustic surveys of fisheries will substantially aid the process of distinguishing different kinds of scatterers. Three specific quantities which may be studied for systematic differences with frequency are the echo integral, echo trace, and target strength distribution.

To aid the comparison process for any one quantity, it would be convenient for the several transducers to sample the identical volume. One way to accomplish this is through the proposed bull's-eye arrangement of transducer elements in concentric patterns. The highest-frequency beam would be formed by a central, circular pattern of elements. The next-highest-frequency beam would be formed by a concentric ring of elements contiguous to the central circle. The lowest-frequency beam would be formed by a second ring of elements surrounding the first, inner ring. The outer diameters of these several areas will be in rough proportion to the respective acoustic wavelengths if sufficiently different. The problem addressed here is the general determination of ring diameters with respect to certain criteria, ultimately to ensure the greatest similarity in sampling volumes.

In presenting and applying design criteria for a three-in-one transducer, the component patterns or arrays of transducer elements are assumed to act as ideal circular or annular pistons. That is, discretized forms of arrays of small elements are ignored. A numerical relation is derived for the 3-dB beamwidth of an annular piston. This is used to determine ring diameters for transducers operating at 38, 120, and 200 kHz, given a constant 3-dB beamwidth of 8 deg. Several performance measures are computed.

METHOD

For the envisaged high-frequency operation of large transducers, a convenient quantity for characterizing relative performance is the beamwidth. Given good measurement conditions, with correspondingly high signal-to-noise ratios for interesting scatterers, the sampling volumes will be very similar for the same beamwidths. For simplicity and definiteness, the basic criterion for determining ring diameters is that the 3-dB beamwidths be identical.

The beamwidth of an annular piston is determined from the beam pattern, $|f|^2$, where f is the relative amplitude of the radiation field in the farfield of the piston. In the usual, and excellent, linear, high-frequency approximation, this is given by the integral of the phase factor $\exp(i\underline{k}\cdot\underline{r}')$ over the piston area A:

$$f = \frac{1}{A}\int_0^{2\pi}\int_a^b \exp(i\underline{k}\cdot\underline{r}')\, r'\, dr'\, d\phi' \quad , \tag{1}$$

where $\underline{k}$ is the wavevector and $\underline{r}'$ is a position vector for the differential element of area $r'dr'd\phi'$ in the annulus extending from r=a to r=b. Performing the integration and substituting $A=\pi(b^2-a^2)$,

$$f = \frac{2}{(b^2-a^2)k\sin\theta}\left[b\,J_1(kb\sin\theta) - a\,J_1(ka\sin\theta)\right] \quad , \tag{2}$$

where $J_1(\cdot)$ is the Bessel function of first kind and first order. This equation is rewritten in parametric form as

$$f = \frac{1}{1-a^2/b^2}\,\frac{2}{x}\left[J_1(x) - \frac{a}{b}J_1\!\left(\frac{a}{b}x\right)\right] \quad , \tag{3}$$

where $x=kb\sin\theta$ and a/b is the ratio of inner and outer radii of the annulus.

The 3-dB beamwidth is determined by solving the equation

$$|f| = 2^{-1/2} \quad (4)$$

for x for given fixed value of the parameter a/b. Numerical results are given in Table 1 together with values of kb for several different half-beamwidths $\theta_{3\ dB}$, measured from the acoustic axis to level of -3 dB, since

$$kb = \frac{x}{\sin \theta_{3\ dB}} \quad (5)$$

Table 1. Solutions of equation (4) for x distinguished by the ratio of inner and outer radii, a/b, and wavenumber-outer radius product kb for four half-beamwidths $\theta_{3\ dB}$ in degrees according to equation (5).

		Half-beamwidth $\theta_{3\ dB}$			
a/b	x	2.5	4	5	10
0	1.616	37.1	23.2	18.5	9.3
0.1	1.607	36.8	23.0	18.4	9.3
0.2	1.581	36.3	22.7	18.1	9.1
0.3	1.541	35.3	22.1	17.7	8.9
0.4	1.490	34.2	21.4	17.1	8.6
0.5	1.432	32.8	20.5	16.4	8.2
0.6	1.370	31.4	19.6	15.7	7.9
0.7	1.307	30.0	18.7	15.0	7.5
0.8	1.245	28.5	17.8	14.3	7.2
0.9	1.184	27.1	17.0	13.6	6.8

For a given inner radius a, frequency, sound speed, and desired beamwidth, the outer radius b is determined in the following manner. The radius b is expressed for each of a range of parameter values a/b. It is also computed according to equation (5). Coincidence at the same parameter value a/b defines the solution. In general, this is found by an iterative procedure seeking an increasing degree of precision.

RESULTS

Dimensions of the several circular and annular pistons are now determined for a half-beamwidth of 4 deg. The reference value of medium sound speed is 1470 m/s, which corresponds to sea water of salinity 35 ppt at temperature 5°C.

(1) 200 kHz The highest-frequency transducer is innermost, with a circular pattern. From the first line in Table 1, with a/b=0, the transducer radius is found to be 2.71 cm.

(2) 120 kHz The intermediate-frequency transducer is annular and contiguous to the central circular core. The inner radius is a=2.71 cm, thus for $\theta_{3\ dB}$=4 deg, the outer radius is b=3.54 cm.

(3) 38 kHz The lowest-frequency transducer is annular and contiguous to the annular piston at 120 kHz. Its inner radius is thus a=3.54 cm. The outer radius for the 4-deg half-beamwidth is b=13.77 cm.

These results are summarized in Table 2. Corresponding measures of directivity (Urick 1983) are included. In terms of the beam pattern $|f|^2$, these are the directivity index for isotropic noise,

$$DI = 10 \log \frac{4\pi}{\int |f|^2 d\Omega} \quad , \tag{6}$$

and directivity index for reverberation,

$$J_v = 10 \log \frac{4\pi}{\int |f|^4 d\Omega} \quad . \tag{7}$$

Both the antilogarithm and logarithmic expressions are used. The equivalent ideal solid-angle beamwidth Ψ is also given, namely

$$\Psi = 10 \log \int |f|^4 d\Omega \quad . \tag{8}$$

In performing the several integrations, only the half space forward of the transducer is considered, as ideal baffling in the opposite direction is assumed.

Table 2. Dimensions and directivity measures of the exemplary three-in-one transducer. The inner diameter is denoted 2a, outer diameter 2b, directivity index for isotropic noise DI, directivity index for reverberation J_v, and equivalent solid-angle beamwidth Ψ.

Frequency	Diameters (cm)		DI		J_V		Ψ	
(kHz)	2a	2b	Antilog	(db)	Antilog	(dB)	Antilog	(dB)
200	0	5.42	539.4	27.3	1165.7	30.7	0.0108	-19.7
120	5.42	7.08	126.5	21.0	853.9	29.3	0.0147	-18.3
38	7.08	27.54	458.8	26.6	1156.7	30.6	0.0109	-19.6

DISCUSSION

According to the rough relation mentioned in the Introduction, the transducer diameters would vary in proportion to their wavelengths, hence $200^{-1}:120^{-1}:38^{-1}$ or nearly 3:5:15. This assumes, however, that wavelengths of contiguous transducers are sufficiently different. Evidently this is not the case for the first and second transducers, with respective frequencies 200 and 120 kHz. Since the heart of the second transducer is empty, being occupied by the first transducer, its beam pattern is sharper than that of its ordinary full-circle version. Thus, to achieve a constant beamwidth, the outer radius can be reduced, in the present case from the estimated 5a/3=4.52 cm to the computed 3.54 cm.

In fact, in the limit that the width of a ring transducer becomes vanishingly small, i.e., as a approaches b,

$$f = J_o(kb \sin \theta) \quad . \tag{9}$$

Solution of the equation $f=2^{-1/2}$ yields the relation

$$kb \doteq \frac{1.125}{\sin \theta_{3\ dB}} \quad . \tag{10}$$

Thus at 120 kHz, a ring of radius 3.2 cm would be sufficient to achieve a half-beamwidth of 4 deg.

No such problem encumbers the determination of the outer radius of the lowest-frequency transducer. The wavelengths corresponding to the inner and outer rings are in the approximate ratio 1:3, hence the outer radius for a/b=0.257 is only slightly less than that of its full-circle version, with a/b=0, cf. Table 1.

The several beams do differ in detail. This is evident from the directivity measures shown in Table 2. The first and third beam patterns are similar, but the measures for the second transducer are distinctly poorer. This is also apparent in the computed sidelobe positions and levels presented in Table 3.

Table 3. Sidelobe positions in parametric form x and as polar angles θ and levels $B=10 \log |f|^2$ in decibels for the transducer defined in Table 2.

Frequency (kHz)	First sidelobe			Second sidelobe			Third sidelobe		
	x	θ	B	x	θ	B	x	θ	B
200	5.135	12.8	-17.6	8.415	21.3	-23.8	11.620	30.1	-28.0
120	4.300	13.7	-8.3	7.875	25.7	-11.7	11.410	38.9	-14.8
38	5.100	13.2	-14.1	8.515	22.4	-29.7	11.485	30.9	-24.5

Different design criteria could be applied. For example, instead of maintaining a constant 3-dB beamwidth, the diameters could be chosen so that the directivity index for isotropic noise remains constant. The directivity index for reverberation or equivalent solid-angle beamwidth, also called equivalent beam angle, could also be fixed. In this case, the sampling volumes would be most similar.

In practice the ideal circular or annular pistons considered here would be replaced by arrays of discrete elements. It has not been necessary to incorporate this in the present analysis, which has aimed at establishing a design procedure. Generalization to discrete arrays is straightforward, as only the form of the beam pattern is changed. A general expression for this, with application to a variety of array types, is given by Foote (1988).

The proximity of the several component transducers and their simultaneous operation at power levels just below cavitation makes nonlinear acoustic effects unavoidable. In particular, directional beams will be formed at the sum and difference frequencies (Westervelt 1963), hence at 320, 238, 162, 158, 82, and 80 kHz. Bandpass-filtering in the several receivers will prevent interference with the primary frequencies, but the possibility of adding additional acoustic elements to sense weaker echoes at other frequencies may be worth considering, especially apropos of plankton measurement.

Given the capacity of the new SIMRAD EK500 echo sounder to operate three different transducers simultaneously, it is reasonable to scrutinize the transducer configuration. The advantage of the proposed bull's-eye design for use at 38, 120, and 200 kHz is that the three beams could sample essentially the identical water volume. The value of this to detailed multiple-frequency analyses of echo integrals, echo traces, and target strength distributions of fish and plankton is clear.

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