DESIGN AND DEVELOPMENT OF A CONSTANT BEAMWIDTH TRANSDUCER FOR SUB-BOTTOM ACOUSTIC PROFILING

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ABSTRACT. The design, fabrication, and acoustic calibration for a new Constant Beamwidth Transducer (CBT) is presented. Although designed for a sub-bottom profiling application, the transducer may be used whenever a spatially constant sound beam is desired over a relatively wide frequency range. The CBT design is based on the theoretical work presented earlier by Van Buren et al. [1] and relies on an axis-symmetric velocity distribution acting over a spherically curved surface. The velocity distribution follows a Legendre shading function that is accomplished by dividing the surface electrode pattern into several discrete concentric rings. Design theory, fabrication, and measured results for a prototype transducer are presented.

I. INTRODUCTION

A new constant beamwidth transducer has been developed for acoustic sub-bottom profiling to be used in the acoustic classification of sediments beneath the ocean floor. For this application, the Constant Beamwidth Transducer (CBT) promises a distinct advantage over "traditional" transducers (ones that vary their acoustic directivity with frequency) by providing a constant acoustic "footprint" of the ocean sub-bottom over a specified frequency range. While the CBT was designed and fabricated for this particular application, it can be used in many other underwater applications as well.

The CBT is based on a concept introduced by Rogers and Van Buren [2]. According to their theoretical analysis, the transducer maintains uniform acoustic loading and a constant directivity pattern with low sidelobe levels above a certain cut-off frequency. It also contains no near field. This is accomplished by controlling the surface velocity of a radiating spherical cap with Legendre function shading. In practice, the velocity shading can be implemented by dividing the spherical cap into several discrete concentric bands, each band with its own prescribed volume velocity. The CBT concept has been verified with an experimental CBT using conventional piezoceramic [1]. This prototype CBT, however, had some significant limitations. Fabrication of the transducer was very difficult and expensive. It was constructed with a mosaic of many small ceramic elements mounted in machined cavities on a spherically shaped backplate. A decoupling material, corprene, was used around and behind each ceramic element in order to reduce edge radiation as well as transverse acoustic and mechanical coupling. Otherwise, undesirable variations would result in the surface velocities and cause beam pattern degradation. The use of the decoupling material imposed a limit on the operational hydrostatic pressure to approximately 500 psi, since above that pressure corprene begins to lose its decoupling properties. The excessive weight of the transducer was also a limitation.

We realized that in order to make the CBT practical and cost effective for use in the sub-bottom profiling system, an alternate piezoelectric material was needed; namely, one that would overcome the fabrication obstacles presented with conventional piezoceramic. A new class of piezoelectric materials called 1-3 piezocomposites was deemed to be a good candidate for this application. The 1-3 piezocomposite is a piezoelectric material consisting of an array of small ceramic pillars embedded in a polymer matrix. Some of the advantages of the 1-3 composite material are that it can be conformed to various shapes and electrode patterns can be readily deposited onto its surface. It also has a lower density than conventional ceramic material and provides a better acoustic impedance match to water. Since the piezocomposite is polarized and electrically connected only in the thickness direction, it has a high transmitting piezoelectric constant (surface displacement per drive volt) and exhibits little transverse mode coupling. Finally, the cost savings of fabricating multiple CBTs promises to be advantageous when compared to the conventional ceramic approach. As a result, we decided to use this material in the new CBT design.

This paper concentrates on the practical issues of designing the CBT with the 1-3 piezocomposite material. Theoretical expressions are kept to a minimum — only those necessary to describe the pertinent design issues. (For a detailed analysis of the theory of CBT, the reader is referred to [1] and [2].) The primary issues discussed in this paper are the design, fabrication, and acoustic testing of the CBT using the 1-3 piezocomposite material. Based on a set of specifications we discuss the basic theory required to

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design the CBT and model its performance. This includes determining the required size of the spherical cap, and predicting the CBT's transmitting response, receiving response, and maximum source level. Some of the relevant fabrication issues that are discussed include the following: selection of the proper 1-3 piezocomposite material (e.g., thickness, volume fraction of ceramic, etc.), conforming the piezocomposite into a spherical cap, application of the electrode pattern, transducer encapsulation, and backing material selection to reduce unwanted back acoustic radiation. The acoustic test results of the CBT are presented and discussed. Included are transmitting and receiving responses as well as beam patterns at different frequencies. This section is followed by a discussion of the experimental results and conclusions.

II. THEORY

We used the following mathematical design formulas and approximations given in [1] and [2] for our CBT design. As mentioned, performance of the CBT depends on controlling the radiating surface velocities along a spherical cap with a Legendre shading function. This shading function is described as

$$\begin{aligned} v(\theta) &= P_{\nu}(\cos\theta), \quad 0 \le \theta \le \alpha_{\nu}, \\ v(\theta) &= 0, \quad \theta \ge \alpha_{\nu} \end{aligned} \tag{1}$$

where α_{ν} is the zero of smallest angle of the Legendre function $P_{\nu}(\cos\theta)$. The order of the Legendre function ν can be chosen to be any real number greater than zero. Thus, the maximum surface velocity occurs at the center of the cap ($\theta = 0$), and the surface velocity diminishes monotonically to zero at $\theta = \alpha_{\nu}$. As illustrated in Fig. 1, the geometrical dimensions of the CBT's spherical cap may be described by the following three parameters (not including the composite thickness): α_{ν}, referred to as the cap half angle; a, the radius of curvature of the spherical cap; and b, the half arc length. These three parameters are simply related by

$$a = \frac{180b}{\pi\alpha_{\nu}}, \tag{2}$$

where α_{ν} is in degrees. The cap half angle, α_{ν}, is defined in terms of Legendre order, ν, by the approximation,

$$\alpha_{\nu} \cong \frac{137.796}{(\nu+0.5)}\left[1 - \frac{0.045}{(\nu+0.5)^2}\right]. \tag{3}$$

Another angular quantity may be introduced that describes the value for θ such that $P^2_{\nu}(\cos\theta) = 0.5$. Physically, this corresponds to the half power angle or the -3 dB point on the mainlobe of the acoustic beam pattern.

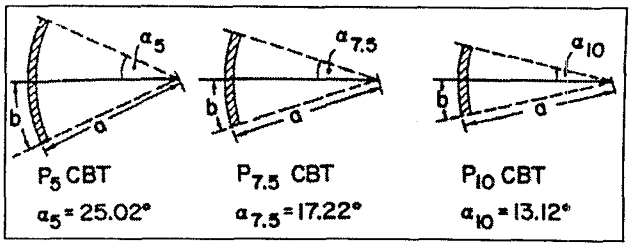

Fig. 1. Geometry of P_5CBT (left), $P_{7.5}$CBT (center), and P_{10}CBT (right).

This can be defined in terms of ν by the approximation

$$y_{\nu} \cong \frac{64.540}{(\nu+0.5)}\left[1 + \frac{0.103}{(\nu+0.5)^2}\right]. \tag{4}$$

The acoustic beam pattern of the CBT at higher frequencies is expected to be rotationally symmetrical, with a predominate mainlobe pointing in the direction of the center of the spherical cap, and falling off in amplitude as one goes away from the axis more or less according to the Legendre function $P_{\nu}(\cos\theta)$. As the frequency decreases, the beam patterns start to look less and less like this; in particular they start to broaden until they can no longer be considered to have nominally the same beamwidth. The frequency at which this happens is called the cut-off frequency, f_c, and is defined by

$$f_c = \frac{c}{1500\,b}\left[1.10 + (\frac{24.6}{y_{\nu}})\right], \tag{5}$$

where f_c is frequency in kilohertz, and c is the sound speed in water. Therefore, the cut-off frequency (f_c)is inversely proportional to the cap radius and increases with a decrease in the -3 dB half angle. In other words, the required cap size is increased by either decreasing the low frequency cut-off and/or decreasing the desired beamwidth. Fig. 2 shows graphically the relationship between these 3 parameters. The practical tradeoffs are readily seen in the increase in fabrication difficulty and overall cost of the CBT.

The transmitting voltage response (TVR) for frequencies below the thickness resonance (in dB re 1μPa/V//m) for the CBT is calculated from the following equation:

$$\begin{aligned} TVR \cong\ & 20\log[10^8\rho c^2 d_{33}(0.618 + \frac{13.8}{y_n}) \\ & (1 + 3.55\times10^{-5} y_{\nu}^2)(\frac{f}{f_c})/y_{\nu}] \end{aligned}, \tag{6}$$

where ρ and c are the density and sound speed of water, respectively, d_{33} is the piezoelectric charge coefficient of the piezoelectric material, and f is frequency. Assuming that the rods of the 1-3 material are closely packed, we can use

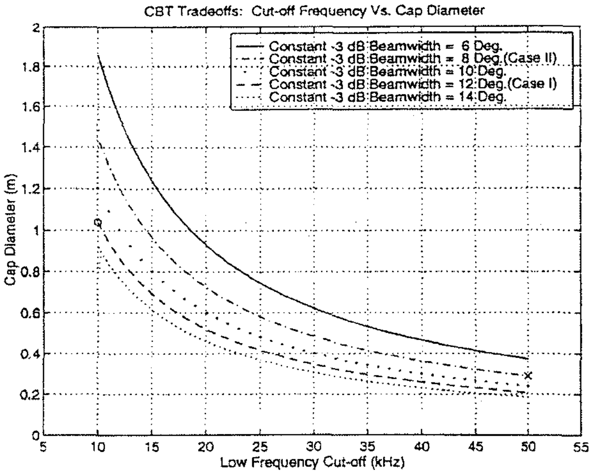

Fig. 2. Relationship between the lowest frequency of operation; i.e., cut-off frequency,the desired beamwidth, and the required spherical cap diameter of the CBT.

the following formula to calculate the corresponding voltage sensitivity, M_O, again for frequencies well below the thickness resonance of the ceramic, thus,

$$2.96\times10^{-5}\frac{\ell d_{33}(f_c/f)(1+6.79\times10^{-5}y_v^2)}{K_{33}^T\varepsilon_0(1.10y_v+24.6)},\quad(7a)$$

where ℓ is the thickness, K_{33}^T is the dielectric constant of the piezoelectric material, and ε_o is the permittivity of free space. In dB re 1V/μPa, the free field voltage sensitivity, *FFVS*, is given as

$$FFVS(dB\ re\ 1V/\mu Pa) = 20\log(M_O).\quad(7b)$$

The directivity index, *DI*, (in decibels) is given in terms of the -3 dB half angle y_v by the approximation

$$DI \cong -20\log(y_v)+40.29+3.09\times10^{-4}y_v^2.\quad(8)$$

III. MODELING

In this section we apply the design equations described in the previous section. The system in which the CBT is employed provides the desired performance specifications. The CBT is required to maintain an 8-degree constant total beamwidth (at -3 dB points) over the frequency range of 50-65 kHz. It must also generate a source level of 205 dB when driven by a power amplifier with a maximum output of 250 watts. The duty cycle is <1%. The maximum depth requirement is 2000 meters and the operational altitude above the sea floor is from 20-40 meters.

The design analysis is begun using the desired total beamwidth of 8 degrees. This gives a value of 4 degrees for the -3 dB half angle y_v. By rearranging (4) and using this value for y_v, the order of the Legendre function ν is calculated to be 15.64 and the cap half angle α_v is calculated from (3) to be 8.54 degrees. Since it is desired for the CBT to maintain a constant beamwidth over the bandwidth of 50-65 kHz, we define the cut-off frequency f_c to be 50 kHz. Next, using the cut-off frequency and the -3 dB half angle the half arc length b of the spherical cap is given in (5) to be 0.145 m. This means that the transducer has an overall "diameter" of nearly 0.3 m (~12 inches). The radius of curvature of the spherical cap a is calculated from (2) to be 0.97 m.

Next, we examine the acoustic performance of the 1-3 piezocomposite CBT. For the purposes of this model we used the following nominal values: material thickness = 0.015 m, the d_{33} is conservatively estimated at 150 x 10^{-12} m/V, and the K_{33}^T = 325. First, *TVR* is calculated from (6). It is plotted as a function of frequency in Fig. 3.

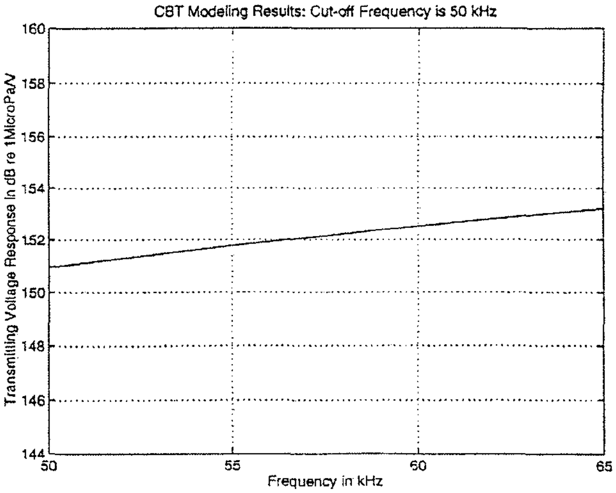

Fig. 3. Calculated TVR for the CBT over the desired frequency range of operation.

The predicted *TVR* has a minimum value of 151 dB re 1μPa/V//m at 50 kHz and increases with frequency at a rate of 6 dB/octave. The minimum value of *TVR* is used to determine whether the desired source level will be attained with the available power amplifier. The maximum achievable source level, SL_{max}, for the CBT may be predicted by knowing the transducer's *TVR*, the input electrical impedance Z_{in} (which depends on the capacitance of the 1-3 piezocomposite), and the maximum available power amplifier output, P_{max}. The maximum source level (in dB re 1μPa) at 1 m is calculated from the following expression:

$$SL_{max} = TVR + 20\log(V_{max}),\quad(9)$$

where

$$V_{max} = \sqrt{P_{max}Z_{in}}\,.$$

The maximum source level generated by the CBT is plotted versus frequency for the case of a maximum power amplifier output of 250 watts. As seen from Fig. 4, the maximum attainable source levels range from approximately 207.5 dB to 208.7 dB re 1μPa at 1 m over the desired bandwidth. This exceeds the minimum requirement of 205 dB.

Since the CBT can also be configured to operate as a receiver, we can calculate the *FFVS* using (7a). A plot of the FFVS versus frequency is shown in Fig. 5. The *FFVS* has a maximum value of approximately -189 dB re 1V/μPa and decreases with frequency at a rate of -6 dB/octave. The directivity index, *DI*, of the CBT is easily calculated using the approximation in (8), resulting in a value of 28 dB.

As mentioned in the theory, the key to maintaining the constant beamwidth is in accurately controlling the velocity distribution along the cap. In practice it is difficult to provide a continuous velocity distribution. Therefore one may choose to apply a stepwise approximation to the Legendre shading function by dividing the cap into *N* concentric bands of either equal area or equal angle. Each band is then driven with a voltage proportional to the average value of the shading function over the band.

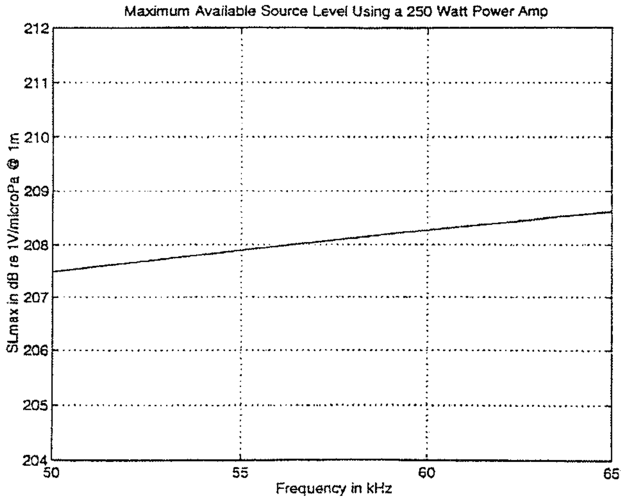

Fig. 4. Maximum achievable source level for the CBT using a 250 Watt power amplifier.

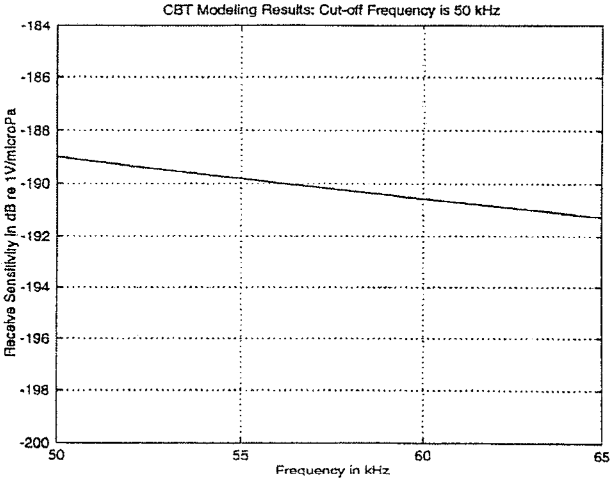

Fig. 5. Calculated receive sensitivity for the CBT.

As a rule of thumb, there should be a minimum of 8 bands, none of which possess angular widths greater than $0.1\alpha_v$ or areas greater than 0.125 times the total cap area. In our case we chose to subdivide the spherical cap into 10 equal angle bands. Instead of applying a different voltage value to each band to provide the shading, we found it more convenient to vary the electrode area of each band and use a single voltage. Here the percentage of band area that was electroded was equal to the average of the shading function over the band. Theoretical analysis showed no degradation in the predicted constant beamwidth properties using this technique. The 10th band required such a thin electrode that we decided to completely cover the 10th band with electroding material instead and use a series capacitor to step down the voltage to give the prescribed amplitude. A schematic of the electrode pattern applied to the 1-3 piezocomposite material is shown in Fig. 6. The basic design parameters of the 1-3 piezocomposite CBT have been now determined. In the next section attention is focused on the fabrication issues of the CBT.

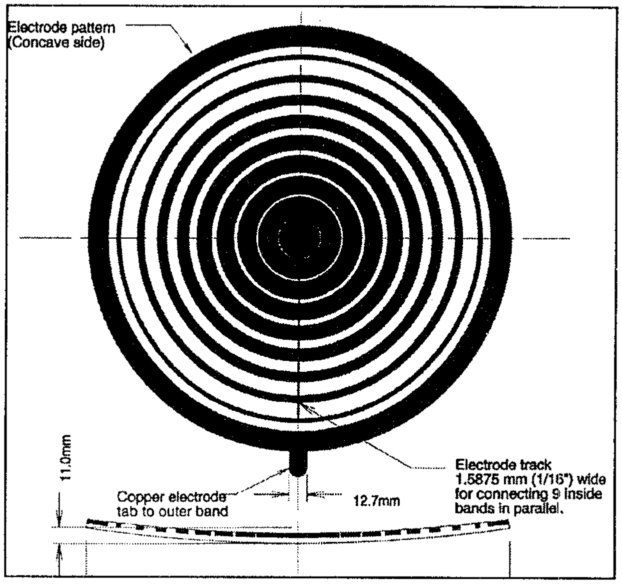

Fig. 6. Electrode pattern used to achieve velocity shading distribution.

IV. TRANSDUCER FABRICATION

Key to the construction of the CBT is the use of injection molded piezocomposite [3]. In particular, the matrix material between adjacent rods was selected to be a thermoplastic which allowed the active substrate to be curved to the desired spherical geometry. The fabrication process begins by selectively electroplating copper on to the flat circular substrate. The plated electrode pattern allows the realization of the desired velocity amplitude shading. Shown in Fig. 7, we used a continuous common front electrode. The next step in the fabrication is to curve the active substrate into a spherical cap segment by warming the layer to approximately 65°C (150°F) and slowly deforming the circular disc between two spherical mold halves. After cooling, the part becomes structurally stable. However, care must be taken to properly support the curved part during the subsequent heat cycles of the fabrication processes, such as the curing of the backing material. The curved component was attached to the housing and sealed along the circumference with 5-minute epoxy. Using the concave half of the deformation tooling a polyurethane window was formed. The window material selected had a room temperature cure therefore avoiding heat related distortion. The transducer backing consisted of lead-loaded rubber chunks interspersed within a syntactic foam-like material. Due to the conformal geometry, the backing was cast and cured in place using the housing cavity behind the active layer as a mold. Again the concave half of the deformation tooling was used to support the curved substrate during the elevated temperature cure. Fig. 8 shows a cross sectional sketch of the finished transducer. A photograph of the 13-inch-diameter CBT prototype is shown in Fig. 9.

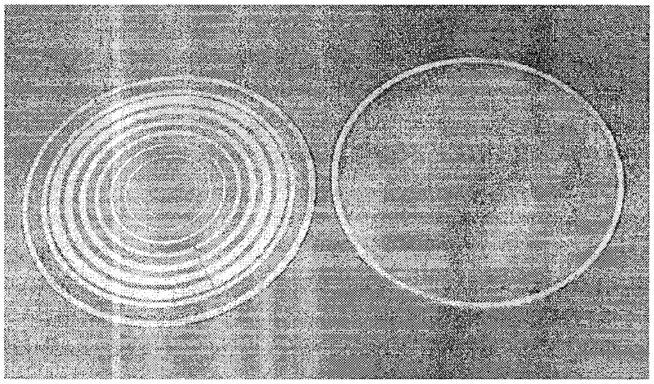

Fig. 7. Photograph of both sides of active electroplated piezocomposite substrate.

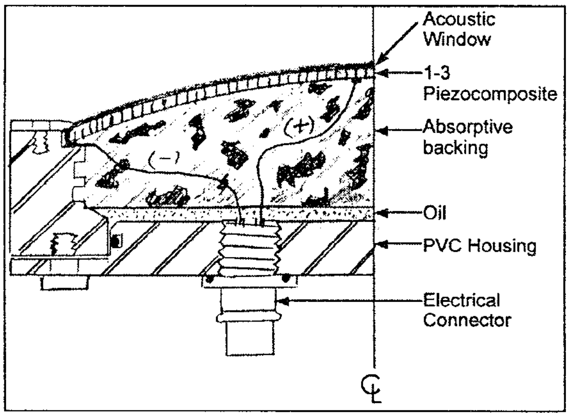

Fig. 8. Cross-sectional view of the transducer configuration.

V. MEASURED RESULTS

The acoustic calibration of the unit shown in Fig. 9 was made at the Naval Undersea Warfare Center's acoustic pressure tank facility in Orlando, Florida. This facility allowed acoustic measurements to be made over a range of temperature and pressure combinations that simulate various ocean environments.

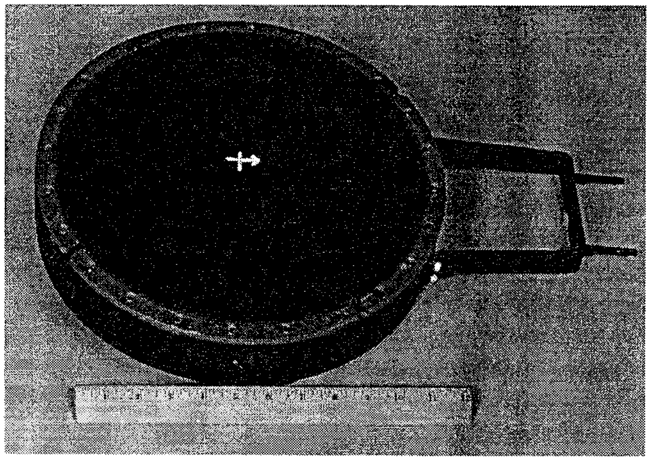

Fig. 9. Photograph of the CBT Prototype.

In general the transducer performance was stable with temperature and pressure. Measurements were taken in both transmit and receive modes. These data indicate the transducer to be a reciprocal device. Fig. 10 shows a typical transmitting response over the frequency range of interest. Fig. 11 shows a typical receive sensitivity response for the same frequency range.

Finally the transmit and receive beam patterns taken at six frequencies of interest are compared in Figs. 12 and 13. Note how the beamwidth remains nearly constant over two octaves of frequency. The transmit patterns shown in Fig. 12 were taken at a hydrostatic pressure of 500 psi at 20°C, whereas the receive patterns were taken at ambient pressure and 3°C. The significant backlobe in the transmit patterns result from the backing material becoming more acoustically transparent with increasing pressure. One also notes the typical frequency dependence of the insertion loss associated with the backing material.

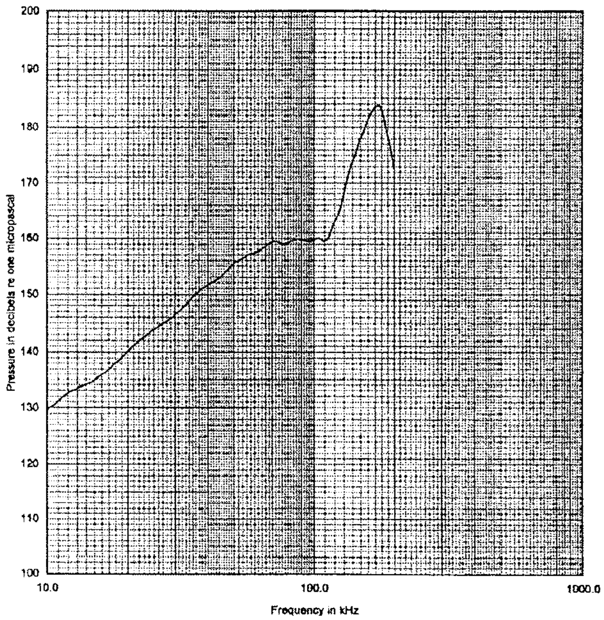

Fig. 10. Measured transmit voltage response.

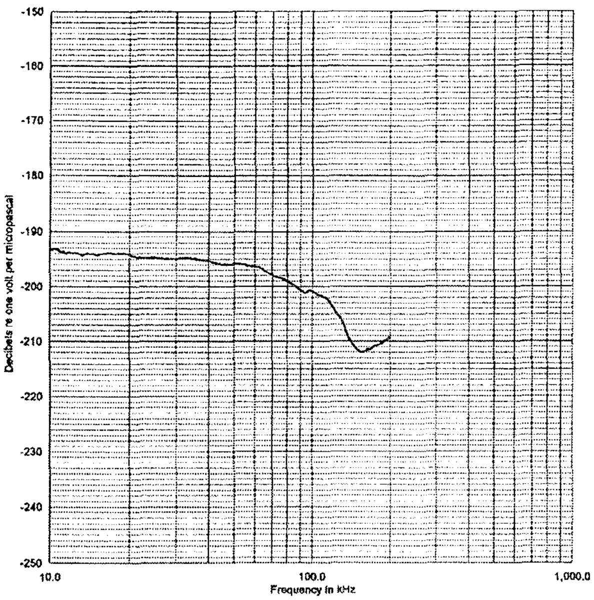

Fig. 11. Measured receive voltage sensitivity.

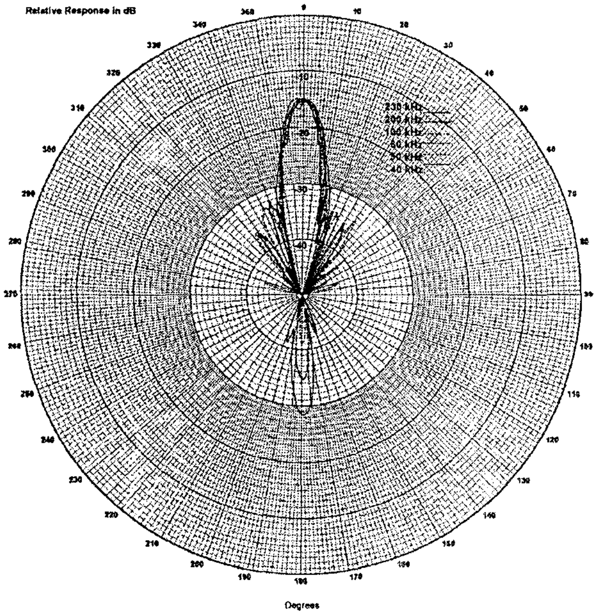

Fig. 12. Measured transmit patterns for 40, 50, 60, 100, 200, and 230 kHz.

VI. CONCLUSIONS

A new type of constant beamwidth transducer has been designed, built, and acoustically calibrated. The device uses a conformable 1-3 piezocomposite material which has been electroplated with copper to realize a velocity amplitude distribution that follows a Legendre function. With this area shading approach, constant beamwidth characteristics were observed for more than two frequency octaves. Although the CBT was developed for an ocean sub-bottom profiling system, this type of transducer can be used for several other applications where a frequency independent spatial response is required.

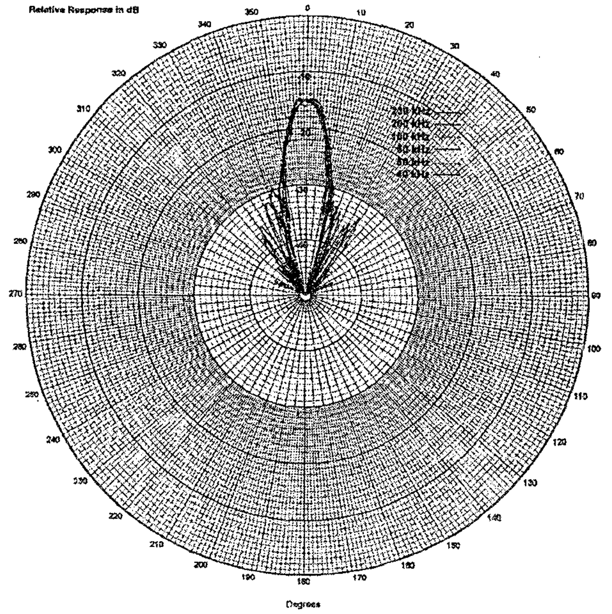

Fig. 13. Measured receive patterns for 40, 50, 60, 100, 200, and 230 kHz.

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