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NEARFIELD CALIBRATION ARRAYS FOR TRANSDUCER EVALUATION

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Introduction

An important feature in the performance of an underwater transducer is the distribution of the sound pressure that is produced in the farfield, i.e., at distances far enough from the transducer so that the angular distribution does not change with increasing range. The farfield pressure distribution cannot easily be measured directly for large aperture transducers because of the large distances involved. This difficulty encouraged efforts to determine the farfield distribution from measurements made in the nearfield of the transducer. One successful method which resulted from these efforts is based on the Trott nearfield calibration array (NFCA) concept [1,2].

The first NFCA's were large planar receiving arrays of small piezoceramic hydrophone elements configured in a square or circular grid [3,4]. The individual element responses of the NFCA are shaded so that it responds to only a single plane-wave component of the sound radiated by a projector placed within a volume in the nearfield of the NFCA; i.e., the array is a plane-wave filter. For planar NFCA's the direction of this component is usually normal to the NFCA. The entire farfield radiation pattern of the projector can then be obtained by rotating it within the nearfield volume.

Trott recognized that a NFCA constructed with reciprocal hydrophone elements and used as a projector would produce a nearly uniform plane wave over the same volume and frequency range for which it is a plane-wave filter. He used this fact to help him obtain suitable amplitude shading coefficients for the first NFCA's. As a projector the NFCA can be used to calibrate acoustic receivers.

In 1973 we derived an analytical expression for the reciprocity principle that is the basis for the success of the NFCA [5]. Using this reciprocity principle we then developed a numerical computer-based procedure that provides an optimum (in a least-squares sense) set of shading coefficients for any NFCA configuration, nearfield volume, and frequency range. This procedure allowed the subsequent development of a steered planar NFCA [6] and a conformal cylindrical NFCA [7].

In this paper we describe the theory, design, construction, and use of NFCA's. We illustrate the concept with two examples. One is a recently developed 5-50 kHz cylindrical NFCA that utilizes only a single line of piezoceramic elements to synthesize a virtual cylindrical array surrounding the transducer and is suitable for measurement tanks as small as about 2.5 m in each dimension. The second is a planar NFCA which we are presently developing that utilizes piezoelectric polymer and is useable up to megahertz frequencies as both a projector and a receiver. This planar NFCA can also be focused to obtain the angular pressure distribution of transducers at distances intermediate between the nearfield and the farfield.

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I. Theory

The theoretical basis for the NPCA concept is the NPCA reciprocity principle [5]. Consider a receiving array consisting of N acoustically small monopole hydrophones. Consider also a volume V in the nearfield of the array (see Fig. 1). If the receiving voltage sensitivities M_n, $n = 1,2,\ldots,N$, of the hydrophone elements in the NPCA are chosen so that for every point $\vec{r}$ in V the following relationship is satisfied

$$\sum_{n=1}^{N} M_n \frac{\exp\left[-ik\left|\vec{r}_n-\vec{r}\right|\right]}{\left|\vec{r}_n-\vec{r}\right|} = M_o\left[\lambda/iD^2\right]\exp(ik\vec{r}\cdot\hat{e}) \ , \qquad [1]$$

then the open-circuit voltage ψ generated in the NPCA due to a radiating sound source placed within V is given by

$$\psi = \left[M_o\lambda/iD^2\right]f(\hat{e}) \ . \qquad [2]$$

Here $\vec{r}_n$, $n=1,2,\ldots,N$, denote the location of the elements in the NPCA, λ is the wavelength, k is the wavenumber $= 2\pi/\lambda$, M_o is unit receiving sensitivity equal to $1V/\mu Pa$, D is a unit distance equal to 1 m, and e is a unit directional vector. The quantity f(e) is the farfield pressure distribution of the sound source, i.e., the acoustic pressure at a farfield distance R, divided by $\exp(-ikR)/R$ to remove the dependence on R. The farfield direction is denoted by the unit vector e. The assumed harmonic time dependence $\exp(i\omega t)$ has been suppressed.

The quantity $\exp(ik\hat{e})$ is a plane wave propagating in the $-\hat{e}$ direction. Thus we can interpret Eq. (1) as requiring that the NPCA, if reciprocal and driven as a projector, produce under free-field conditions a plane wave throughout a finite volume V in its nearfield. Equation (2) states that the NPCA is a plane-wave filter for sound emanating from within V. The NPCA need not actually be reciprocal. The requirement of Eq. (1) is based strictly on the receiving properties of the NPCA. However, if the NPCA is reciprocal, it can also be used without adjustment as a projector to produce a plane-wave region for calibrating receiving transducers and arrays. Otherwise, the elements of the NPCA must be readjusted so that their transmitting current responses S_n satisfy an equation similar to Eq. (1).

It is convenient to replace M_n in Eq. (1) by $M'_n\exp(ik\vec{r}_n\cdot\hat{e})$ where the factor $\exp(ik\vec{r}_n\cdot e)$ is the shading necessary to phase the NPCA to the plane normal to e that passes through the origin chosen for $\vec{r}_n$. We also move the factor λ/D^2 to the left-hand side of Eq. (1) and call the combination M'_nD^2/M_o the NPCA shading coefficient W_n. These coefficients provide the shading, in addition to $\exp(ik\vec{r}_n\cdot e)$, that is required to produce plane-wave conditions throughout V.

An optimum set of shading coefficients can be obtained as follows for any NPCA configuration with a prescribed plane-wave direction e, volume V, and frequency range Ω. Here a point $\vec{r}$ and an angular frequency ω are selected randomly from V and Ω, respectively, and substituted into Eq. (1) to form a linear equation in the N unknowns W_n, $n = 1,2,\ldots N$. We repeat the procedure M times until an over-determined set of simultaneous equations (i.e., $M>N$) is obtained. We then obtain values for the shading coefficients W_n as the least-squares solution to the M equations. When M is much larger than N (typically M is chosen greater than about 10N) and when V and Ω are well represented by the random choices for $\bar{r}$ and ω, the least-squares solution will tend to stablilize. At this point, an increase in M will not increase significantly the plane-wave uniformity, even though the individual shading coefficients may change somewhat. The optimum set of shading coefficients is taken to be the solution when stabilization has occurred. This method is best implemented using a digital computer such as the VAX-11/780 at NRL-USRD. The shading coefficients are usually complex numbers, representing both amplitude and phase shading (in addition to the factor $\exp(ik\bar{r}_n \cdot e)$). Real shading coefficients can be obtained by separating Eq. (1) into real and imaginary parts and solving the resulting 2M simultaneous equations. The plane-wave uniformity produced using real coefficients will be somewhat less than that produced using the corresponding complex coefficients. The shading coefficients should be evaluated by back substitution to determine if they produce acceptable plane-wave uniformity throughout V and Ω. If they do not, then either the array configuration must be changed or the nearfield volume and/or frequency range reduced.

II. 5-50 kHz Synthetic Cylindrical NFCA

The cylindrical NFCA, as shown in Fig. 2 together with a piston transducer to be calibrated, consists of a number of identical, parallel, straight-line hydrophone arrays, all normal to e and configured to a circular cylinder surrounding the desired nearfield volume V. Rather than constructing the entire cylindrical array, it is far easier to synthesize it by using only a single line array. To do this we rotate the transducer to be calibrated about an axis parallel to the line array and make measurements at each of the angular positions corresponding to a line in the cylindrical NFCA.

Shading coefficients for the cylindrical NFCA are best obtained using a two-step version of the procedure described in Sec. I. First we obtain shading coefficients α_q, $q = 1,2,\ldots,Q$, for the elements in each line so that the line produces a nearly uniform outgoing cylindrical wave throughout the desired volume V and frequency range Ω. The same set of coefficients is used for each line, both for reasons of symmetry and in order to use a single line to synthesize the cylindrical NFCA. Next each line in the NFCA is shaded externally; i.e., the same coefficient β_ℓ is applied to every element in the ℓth line so that the cylindrical NFCA produces a plane-wave throughout V in the azimuthal direction e. As described above, the plane-wave phase term $\exp(ikr_{\ell q} \cdot e)$ is factored from the shading coefficients. The resultant shading coefficient for each hydrophone (ℓ,q) is given by the product $\beta_\ell \alpha_q$.

The shading coefficients α_q are permanently installed during construction of the line. The external line shading, however, is applied, via computer software, by multiplying each of the coefficients β_ℓ, together with the appropriate plane-wave phase factor, times the corresponding measured response at the ℓth line position in the NFCA and summing the L products to obtain the NFCA response. Using a single line array to synthesize the cylindrical NFCA allows us to tailor the NFCA configuration to the transducer to be calibrated. We can vary the NFCA radius and the number of lines in the array over very broad limits and compute external line shading coefficients that are appropriate for the selected NFCA configuration.

We chose the line of hydrophone elements used to synthesize the cylindrical NFCA to be 1.1938 m (47 in.) long and to contain 48 piezoceramic elements spaced 2.54 cm apart, center-to-center. The elements are capped PZT-4 ceramic cylinders 1.27 cm both in diameter and length. They are suspended in circular rubber mounts that are centered in a cylindrical wire framework designed to ensure that the elements are accurately positioned in the line. The entire framework is encased in a butyl rubber tube and filled with deaerated castor oil. The line is suitable for NFCA operation over the frequency range from about 5 kHz to 50 kHz. It is convenient to establish a cylindrical coordinate system (r,θ,z) relative to the line array centered along the z-axis. We chose the cylindrical-wave volume to be that contained within the planar boundaries $z=-0.3$ m and $z=+0.3$ m, the inner cylindrical surface $r=0.1$ m, and the outer cylindrical surface $r=0.6(f/f_o)^{1/2}$ m, where $f_o=5$ kHz and f (equal to $\omega/2\pi$) is the desired frequency. Thus the outer radial limit of the nearfield volume increases from a minumum of 0.6 m at 5 kHz to 1.9 m at 50 kHz. This increase translates into potentially larger radii for the cylindical NFCA at higher frequencies and is consistent with a corresponding increase in the Rayleigh distance for the line.

For convenience, we normalized the shading coefficients by the element spacing and set the shading coefficient for each of the center 20 elements equal to unity, with no noticeable sacrifice in the resulting cylindrical-wave uniformity. We then computed the remaining 14 unique coefficients (using top-bottom symmetry) based on 600 random selections of both frequency and nearfield position. We computed real element shading coefficients for the line primarily because it is easy to implement amplitude shading passively. When we formed the over-determined set of equations to compute the internal shading coeffients, we first selected the frequency randomly from 5 to 50 kHz, adjusted the outer radial limit of the nearfield volume accordingly, and then selected the position randomly from within the resulting nearfield volume. The resulting values α_q, $q=1,2,\ldots,48$, vary from 0.195 to unity. We evaluated the cylindrical-wave uniformity produced by these shading coefficients throughout the frequency range from 5 to 50 kHz and the specified nearfield volume and found an average variation of about 3 percent in amplitude and 2 degrees in phase.

We implemented the element shading α_q during construction of the nearfield line array as follows. First we purchased a large number of ceramic cylinders representing several wall thicknesses. We then measured their sensitivity M and capacitance C and selected cylinders whose relative MC product was equal (or nearly so) to each of the coefficients α_q. Since we intended to connect all of the elements in the line electrically in parallel, their individual responses add to the NFCA response according to their MC product rather than their sensitivities. We were able to match 40 of the coefficients in this manner. We matched each of the remaining 8 coefficients by adding a small capacitor in series with a cylinder.

We tested the nearfield line array in NRL-USRD's pressure tank by using it to calibrate a large piston-type transducer, called the XP4A, whose diameter is 46 cm. The pressure tank is an enclosed circular cylinder of length 8 m and diameter 2.5 m. We suspended both the XP4A and the nearfield line vertically near one end of the tank with their axes 50 cm apart. The choice of 50 cm for the radius of the cylindrical NFCA is somewhat arbitrary; it could have been as small as about 35 cm for the XP4A. The XP4A was driven electrically by a pulsed sinusoid of the desired frequency and with a pulse length sufficiently long to ensure steady state both acoustically and electrically but short enough to avoid interference from unwanted acoustic reflections from the boundaries of the tank. The open-circuit voltage developed in the line was measured at 360 angular positions, 1 degree apart, as the XP4A as rotated. The measured signal was digitized and passed to a PDP-11/60 computer where it was analyzed using the Discrete Fourier Transform (DFT) to obtain the equivalent CW amplitude and phase of the received signal for each angle of rotation.

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Prior to processing the acquired data, we computed the external shading coefficients β_ℓ, $\ell=1,2,\ldots,L$, necessary to synthesize the full cylindrical NPCA. To ensure that the lateral spacing between lines not exceed 0.8λ, we chose L = 30 for frequencies from 5 to 10 kHz and L = 120 for frequencies from 10 to 50 kHz. We found that only the 180 degree sector of the cylindrical array centered about the desired azimuthal direction e is useful in producing a plane-wave region. This allowed us to reduce L to 16 for frequencies from 5 to 10 kHz and to 61 for frequencies from 10 to 50 kHz. In addition, right-left symmetry reduces the number of unique shading coefficients to 8 and 31 respectively. We obtained shading coefficients for each of the two frequency ranges by forming 400 over-determined equations in the unknowns β_ℓ.

We then processed the acquired data with the shading coefficients to obtain the azimuthal farfield pressure distributions. Results for 5, 10, 20, and 40 kHz are shown in Figs. 3-6. The solid curves are distributions measured in a lake at a farfield distance of 14.3 m. The X's indicate computed farfield values obtained using the synthetic cylindrical NPCA. Computed farfield values at angles intermediate to those shown here are in equally good agreement but are not shown in order to avoid cluttering the curves. The small differences between the results at 5 kHz are believed to be real since the lake results were obtained 1 year prior to the NPCA results. The even better agreement between the NPCA and the lake results at higher frequencies supports this view.

III. Piezoelectric Polymer NPCA

As the frequency of operation increases above 50 kHz, it becomes more difficult to construct NPCA's using conventional piezoelectric ceramic elements. One reason for this is the increased positional accuracy that must be maintained at higher frequencies. Also, with a higher density of elements (the spacing between elements must not exceed about 0.8λ), the required acoustic transparency of the NPCA becomes more difficult to achieve. Fortunately, recent advances in piezoelectric materials provide an alternative to discrete ceramic elements.

We are presently constructing a small prototype (0.24 m in diameter) of a planar NPCA utilizing piezoelectric polymer PVDF as the active material. Unlike earlier receive-only NPCA's, this one will also be useable as a projector. The design is shown in Fig. 7. The PVDF is attached to a backing plate fabricated from a rigid plastic material that is made as acoustically transparent as possible. The use of a material that is acoustically transparent eliminates potential measurement problems due to standing waves between the transducer and the NPCA. A thin printed circuit board with a bulls-eye electrode pattern is sandwiched between the PVDF and the backing plate. The common ground electrode for the PVDF is provided by a cover sheet of nonpiezoelectric PVDF that is fully electroded on one side. Separate electrical leads are brought out of the NPCA for each of the annular bands, and the NPCA shading, one coefficient per band, is applied externally. We note that the use of a continuous array rather than discrete hydrophone elements greatly extends the upper frequency limit of the NPCA. For PVDF as the active material, this limit can be above 1 MHz.

The PVDF NPCA was conceived originally for use in NRL-USRD's pressure tank for calibrating high-frequency transducers such as high-resolution sonar receiving arrays. Since high-resolution sonars are often used in situations where targets are located at distances intermediate between the nearfield and farfield of the receiver, it is useful to be able to determine the angular pressure distribution of the receiver at these intermediate distances. We have recently developed a generalized version of the NPCA reciprocity principle that applies to this case. As indicated in Fig. 8, the NFCA is shaded to produce, throughout the nearfield volume V, a uniform spherical wave that appears to diverge from the field point $\bar{R}$. When the NFCA is used to calibrate a transducer placed within V, the resulting angular pressure distribution corresponds to the field position $\bar{R}$. We obtain the conventional NFCA by letting the field position approach infinity so that the spherical wave becomes planar. We have tested this focused NFCA concept numerically and found that shading coefficients appropriate for plane-wave conditions are equally suitable for focusing if we multiply the shading coefficient for each annular band by the phase factor $\exp[ik\{(|\bar{R}|^2+d_n^2)^{1/2}-|\bar{R}|\}]$, where d_n is the radial distance from the center of the bullseye electrode pattern to the center of the band. This approach does not work very well when $|\bar{R}|$ becomes very small. However, in this case we can make direct measurements of the pressure distribution and do not need a NFCA. The PVDF NFCA has many other applictions as a plane-wave projector and/or receiver. For example, it can be used to perform farfield scattering measurements in small measurement tanks.

IV. Summary

The NFCA is a proven concept for determining the farfield performance of underwater transducers from measurements made in the nearfield of the transducer. The NFCA can be used as either a receiver for calibrating projectors or as a projector for calibrating receivers. We have developed a cylindrical receiving NFCA suitable for operation from 5 to 50 kHz that can be used in measurement tanks as small as 2.5 m in each dimension. We are also developing a planar NFCA utilizing PVDF as its active material that can be used up to megahertz frequencies as both a projector and a receiver. This NFCA can also be focused in order to determine the angular pressure distribution of transducers such as high-resolution sonar receivers at distances intermediate between the nearfield and the farfield.

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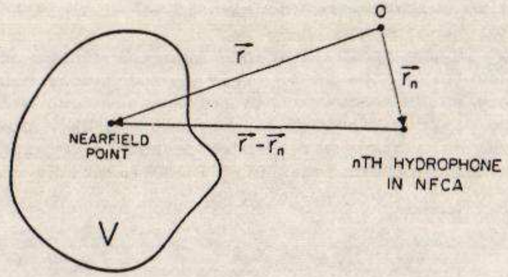

Fig. 1. Geometry of the problem.

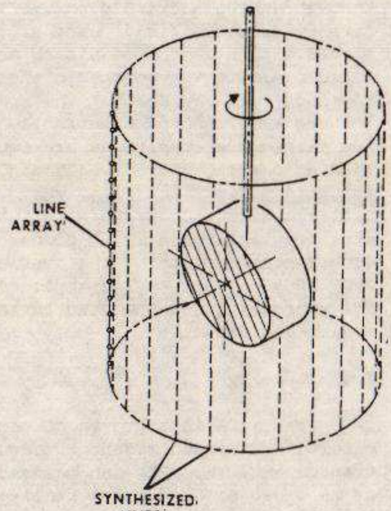

Fig. 2. Cylindrical NFCA.

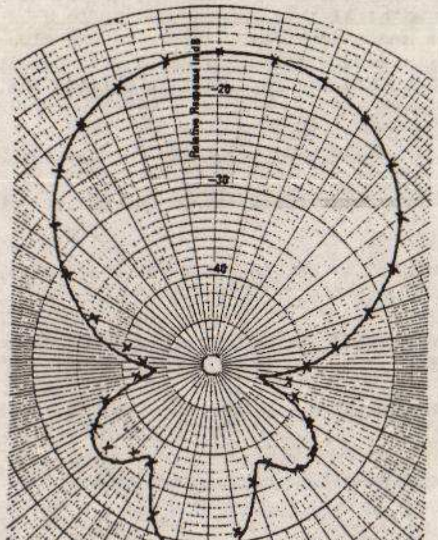

Fig. 3. Farfield pressure distribution at 5 kHz: —— directly measured; X NFCA results

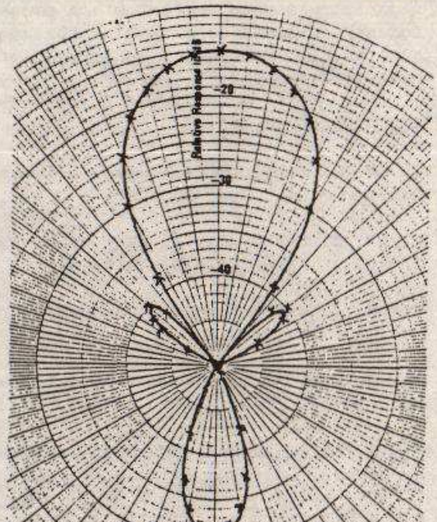

Fig. 4. Farfield pressure distribution at 10 kHz: —— directly measured; X NFCA results.

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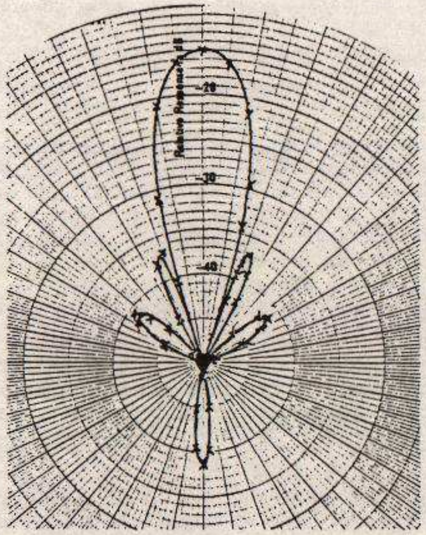

Fig. 5. Farfield pressure distribution at 20 kHz: — directly measured; X NFCA results.

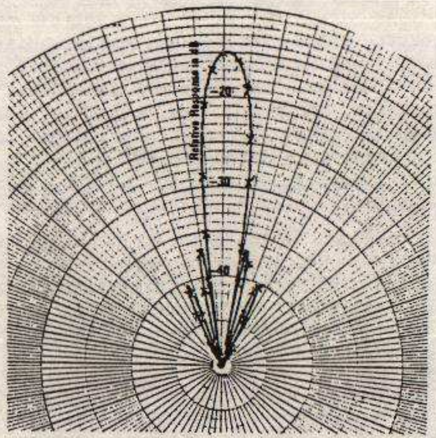

Fig. 6. Farfield pressure distribution at 40 kHz: — directly measured; X NFCA results.

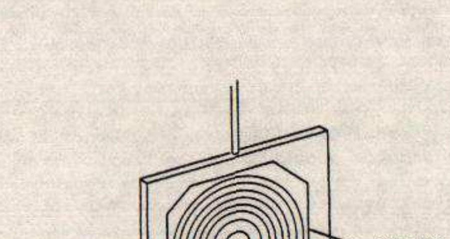

Fig. 7. PVDF NFCA

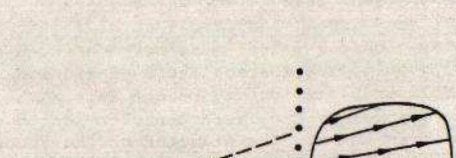

Fig. 8. Focusing NFCA