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INTER-ELEMENT COUPLING IN ARRAYS OF LARGE-AREA HYDROPHONES

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INTRODUCTION

In recent years, there has been a great deal of interest in the development of large-area hydrophones for passive sonar applications. Such developments became possible partially due to the availability of piezoelectric poly-(vinylidene fluoride) thick films (PVDF). PVDF is attractive because it offers the combined properties of low density, mechanical strength and flexibility, and good impedance match to water. Hydrophone arrays can readily be fabricated by using the state-of-the-art PVDF [1] to provide adequate sensitivity for acoustic detection covering a large active surface with closely packed elements. However, current PVDF materials are processed by extrusion followed with a uniaxial stretching and poling. This results in a very strong in-plane anisotropy in their piezoelectric properties. The inequality between the "31" and the "32" properties has been shown to cause the hydrophone elements to be extremely sensitive to in-plane flexural motions, leading to a strong inter-element coupling that prohibits proper beam steering [2]. Specifically, upon acoustical illumination, the phase difference between elements shows a large deviation from the ideal phase difference for two uncoupled point elements located at the centers of the PVDF sheet elements. In this paper, this deviation in transfer phase is investigated experimentally in simple arrays of PVDF hydrophones. A new piezoelectric ceramic-polymer composite that exhibits much smaller planar anisotropy is also used in this study of the inter-element coupling of large-area hydrophones.

EXPERIMENTAL

The PVDF samples used were manufactured by Thorn EMI via a uniaxial stretching process. The thick voided sheets were poled in the thickness direction, and elctroded with a vacuum-deposited copper film, which was about 1 mm thick over the 0.64 mm polymer. The properties of this material have been reported by McGrath et al [3]. The piezoelectric "31" coefficient in the stretched direction has a considerably greater value than the corresponding "32" coefficient. Arrays of PVDF hydrophones were fabricated by using 6.35 cm x 6.35 cm square pieces bonded to a 2 mm-thick common aluminum plate. Each two PVDF squares on top and bottom of the plate formed one hydrophone element, oriented in two different designs. In one case, the stretched directions of the top and the bottom pieces were aligned in parallel, and this will be designated as the "parallel" design. In the other, the stretched directions of the PVDF squares were perpendicular to each other and hence designated as the "cross" design. The purpose of the central stiffening plate is to minimize the planar flexural motions of the PVDF sheets during thickness-mode compression, in order to obtain a constant receiving sensitivity over a wide frequency range. A theoretical analysis of this central-stiffening design for PVDF hydrophones was recently given by Thompson, Geil and Shields [4]. The top and the bottom PVDF sheets were connected electrically in parallel with the high-side outward. This arrangement has the advantage of doubling the hydrophone capacitance, but, for the purpose of shielding a copper screen has to be used above and below the hydrophone element when encapsulated. The 1x4 arrays of these two types of square hydrophones were encapsulated by using a polyurethane called the Conathane EN-12. The gap size between the hydrophones was maintained at a nominal value of 1.27 mm.

The planar anisotropy of the uniaxially-oriented PVDF sheets was recognized as a difficulty in the design of PVDF hydrophones. Its temperature instability at temperatures higher than 70 C is also a limitation in the selection of encapsulants for PVDF hydrophones because the encapsulant can not be cured at higher temperatures. Therefore, it is desirable to identify alternative materials that do not exhibit the planar anisotropy of PVDF and have an improved temperature stability as well. In this study, a polymer-ceramic composite was also used for comparing the result with that obtained from the PVDF arrays. The material was manufactured by the NTK Technical Ceramics of Japan, having the designation of NTK-306 Piezorubber. Basically, fine lead titanate particles were uniformly dispersed in a neoprene rubber matrix at approximately 60% loading. A conductive neoprene sheet, 1 mm thick, was bonded to the composite and used as the electrodes. The properties of this "0-3" connectivity composite [5] were described in Ref.s [6] and [7]. A composite hydrophone array was fabricated in a sandwich construction similar to the design of the PVDF arrays, except that the central stiffening aluminum plate was replaced by a very thin G-10 fiber-glass plate (0.13 mm thick) for mounting of the hydrophones. Calculations [4] showed that this non-metallic thin plate offered practically no stiffening effect when comparing with the modulus of the PVDF sheets themselves. This was used as a common plateform for mounting and thus greatly facilitated the array fabrication. The fiber-glass plate at the center also allows the hydrophone elements to be connected with the high-side inward to provide self-shielding for the array.

The arrays were tested at the Naval Research Laboratory's USRD Lake Facility and the Anechoic Tank Facility. The free-field voltage sensitivity of each hydrophone and that of the arrays (with all elements connected electrically in parallel) were measured. As a measure of the inter-element coupling in the array, the transfer phase of one hydrophone relative to its adjacent neighbor was determined, while the array was tilted at an angle θ toward the sound source. Theoretically, the ideal phase difference in this arrangement for two uncoupled point elements located at a distance d apart is

$$\text{Phase (degree)} = [f\ d\ \sin\theta\ /c] \times 360 \qquad (1)$$

where c is the sound speed in water and f the frequency. For given d and θ, the transfer phase is linearly proportional to the test frequency. For the results reported here, θ = 45 degrees.

RESULTS AND DISCUSSION

In order to validate the measurement technique, four USRD F-42 standard ceramic hydrophones were first placed in the Lake facility as a 1x4 array of point hydrophones 45 -degree to the incoming sound wave. The center-to-center distance was set equal to that in the PVDF hydrophone array. Figure 1 shows the transfer phase data measured over the frequency range of 1 - 10 kHz for these F-42 hydrophones. The result clearly agreed very well with the expected relation given in Eq. (1). Any small deviation from the theoretical values may be due to the uncertainties in hydrophone positioning by freely hanging them in water at a 4-meter depth for testing.

The free-field voltage sensitivity of PVDF hydrophones was constant at -203 dB re 1 V/μPa up to the frequency of 10 kHz. The transfer phase result for the two PVDF arrays is given in Fig. 2. For the "cross-design" PVDF hydrophones, the phase difference between adjacent elements greatly deviates from the theoretical prediction for point hydrophones. The only acceptable result in this case is at the high frequency end. As the frequency decreases, the phase is off from the theoretical line by as much as 40 degrees. This is indicative of a very strong inter-element coupling between these hydrophone elements. On the other hand, the "parallel-design" PVDF hydrophones showed transfer phase differences in agreement with the calculation of Eq. (1). The deviation from the theoretical line is less than ±5 degrees over the entire frequency range of 1 - 10 kHz. This result was also shown to be independent of pressure up to 3.5 MPa. The difference in the phase response of these two designs may be attributed to the fact that in the "parallel" case the hydrophone element is symmetric with respect to the neutral plane, which falls in the center plane of the aluminum stiffening plate. As the element deformed in response to any spurrous in-plane flexural motions due to the presence of the plate and the coupling through the polyurethane encapsulant, the tensile and the compressional stress components in the top and the bottom PVDF sheets simply cancelled out each other. The hydrophone therefore responded in a pure hydrostatic mode and acted as the acoustical sensor intended for by the design. The central-stiffening of PVDF for large-area hydrophone application also has the advantage of requiring less stiffening than the double-sided stiffening designs reported in the literature previously [8]. This is an important consideration in large-scale applications, because the penalty from the added weight to the array becomes much less.

The phase response of the NTK-306 composite hydrophones is shown in Fig. 3. The result is in excellent agreement with the theory over the entire frequency range tested. The deviations are much less that the ±5 degrees observed in the case of the "parallel-design" PVDF hydrophones. It is worth noting that the composite hydrophone array used a thin fiber-glass central plate versus the thick aluminum stiffening plate for the polymer hydrophone arrays. The good performance of the composite hydrophones is definitely related to the low values of thier piezoelectric "31" and "32" coefficients, which are also equal to each other. The sample was 3 mm thick, and therefore offered sufficient stiffness without additional stiffening. The material properties were shown earlier to be independent of pressure up to 35 MPa [7]. The hydrophones had a constant sensitivity of -206 dB re 1 V/μPa up to 10 kHz. When tested up to 7 MPa, there was no change in either their sensitivity or phase response.

CONCLUSION

Large-area hydrophones were fabricated by using both Thorn EMI PVDF and the NTK-306 Piezorubber in a centrally-stiffened sandwich design. In the case the PVDF sheets were mounted in a crossed configuration, the inter-element coupling between hydrophones was shown to be significantly strong, as measured by the transfer phase difference between the adjacent hydrophones. When a parallel design was used, the inter-element coupling was greatly reduced, even with the presence of a common central aluminum plate. This improvement was attributable to the symmetry preserved in this latter design. However, the best phase response was obtained in the composite hydrophone array, with a performance approaching the theoretically-predicted behavior of point hydrophone arrays. This feature shows that the "0-3" type piezoelectric composite is a very attractive candidate for large-area hydrophone applications.

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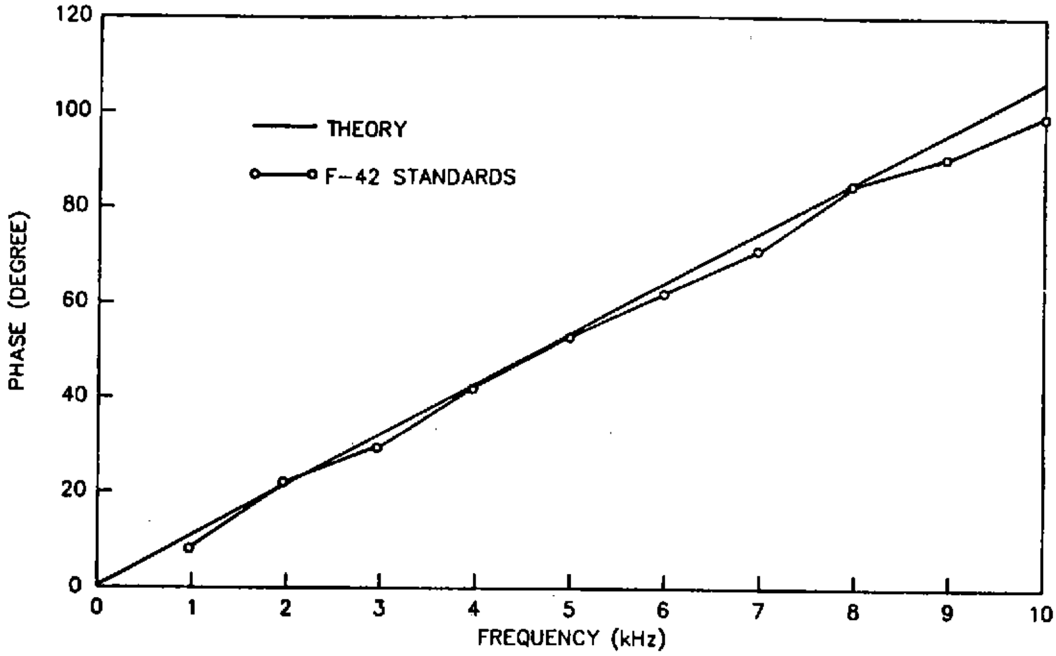

Fig. 1: Transfer phase of F-42 point hydrophones as a function of frequency.

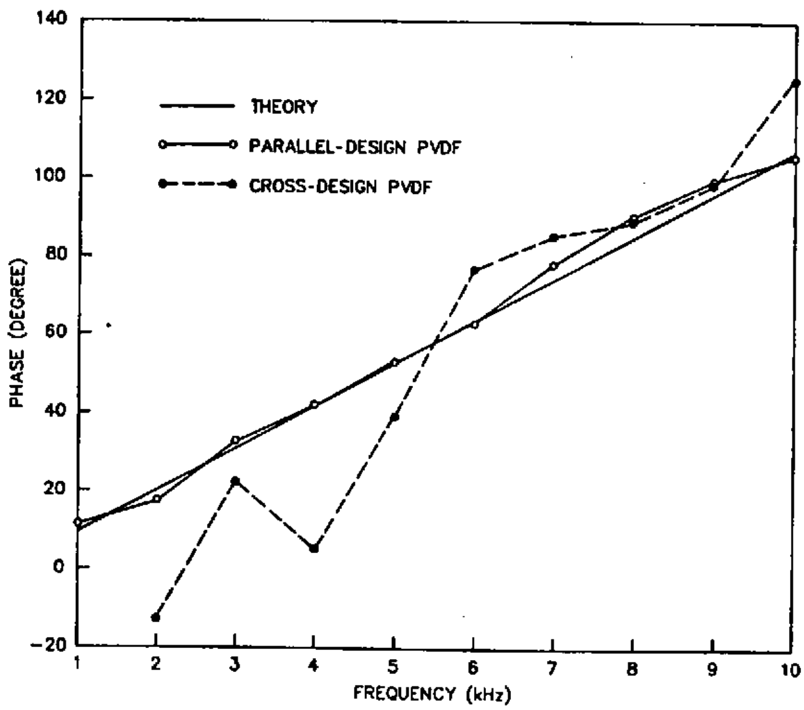

Fig. 2: Transfer phase of PVDF hydrophones as a function of frequency.

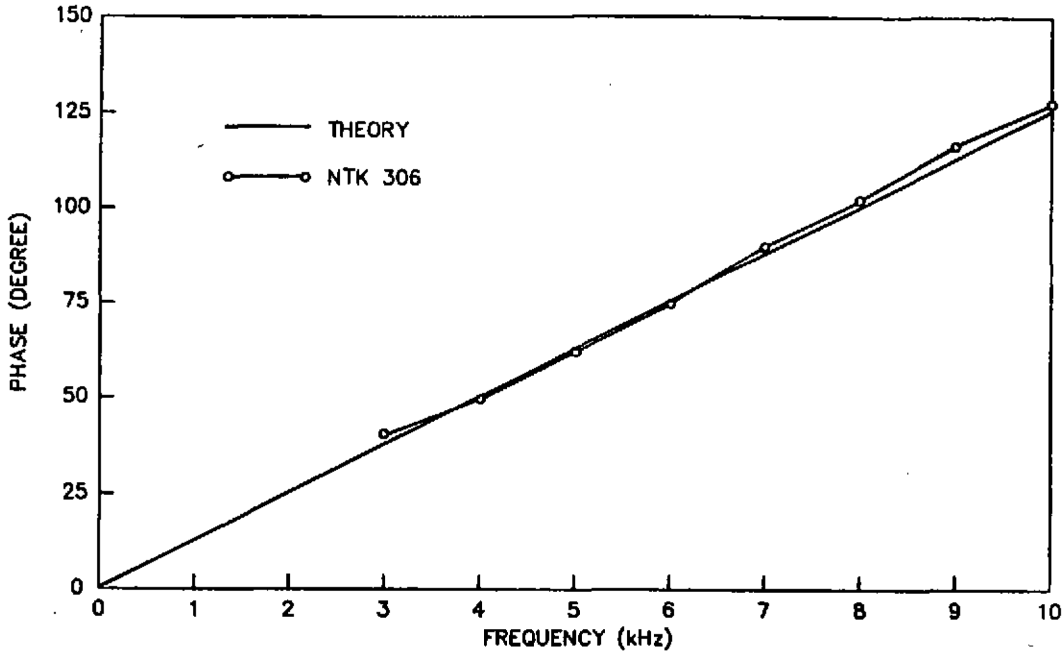

Fig. 3: Transfer phase of NTK-306 composite hydrophones as a function of frequency.