PT/P(VDF-TrFE) hydrophone array

Sien Ting Lau, Kin Wing Kwok and Helen Lai Wah Chan

Department of Applied Physics and Materials Research Centre,
The Hong Kong Polytechnic University, Hunghom, Hong Kong, China

ABSTRACT

0-3 composite thin films of lead titanate (PT) in poly(vinylidene fluoride-trifluoroethylene) (PT/P(VDF-TrFE)) have been prepared by the spin-coating method. The piezoelectric coefficients of PT and P(VDF-TrFE) have opposite signs, while their pyroelectric coefficients have the same sign. The two phases of the composite film are then poled in opposite directions to prepare a piezoelectric film with vanishing pyroelectric response. An 8-element hydrophone array with this composite film as the sensing elements have been fabricated and characterized. The array has good receiving sensitivity over several MHz. The angular responses of the array elements are measured and the results are compared to a theoretical model. The acoustical and electrical cross-coupling between the array elements are also discussed.

Index Terms — PT, P(VDF-TrFE), Composite, Hydrophone

I. INTRODUCTION

The increasing sophistication of ultrasonic techniques for non-destructive testing (NDT) of various materials, including human body, has brought an increasing concern for precise measurements of the ultrasonic fields in the megahertz frequency range. Hence, considerable effort has been put into the development of a high performance hydrophone [1] or hydrophone array [2]. If an array is used, mechanical scanning of the hydrophone is not required. By constructing a system [2], the acoustic waveform can be captured and presented on a microprocessor display in real time.

Piezoelectric 0-3 composites with piezoelectric ceramic powder embedded in a passive polymer matrix have a considerable potential in sensor applications as they combine the good piezoelectric properties of the ceramic with the good mechanical properties of the polymer [3-4]. Recently, 0-3 composites with ceramic particles in a piezoelectric polymer matrix have also received increasing attention [5-7]. The piezoelectric coefficients of the ceramic and polymer have opposite signs while their pyroelectric coefficients have the same sign. Our previous report [8] shows that, by poling the two phases in opposite directions, the piezoelectric activity of the composite can be enhanced while the pyroelectric activity is reduced. Therefore, it is feasible to use this material for constructing hyrophones with good receiving sensitivity and low response to temperature fluctuation. In the present work, we have prepared PT/P(VDF-TrFE) 0-3 composite films with the two phases poled in opposite directions, and the performance of an 8-element hydrophone array fabricated using this film has been evaluated.

II. PREPARATION of 0-3 PT/P(VDF-TrFE) COMPOSITES

The lead titanate (PT) powder was prepared by a sol-gel method [9], and was annealed at 800 °C for 1h. The average crystallite diameter of the powder was about 60 nm. The vinylidene fluoride-trifluoroethylene (P(VDF-TrFE) copolymer with 70 mol% of VDF, supplied by Piezotech Co., has a Curie temperature of 105 °C upon heating and a melting temperature of 149 °C. To prepare 0-3 composite films, the copolymer pellets were first dissolved in methyl-ethyl-ketone (MEK), and a suitable amount of PT powder was blended into the solution and dispersed by ultrasonic agitation. The resulting mixture was then spin-coated on aluminum/ glass substrate to produce a film with a thickness of about 6 μm. After drying the composite film at room temperature, the film was annealed at 120 °C for 2 h to remove the solvent and to increase the crystallinity of the copolymer phase. An aluminum top electrode was then evaporated onto the surfaces of the film to produce a capacitor structure. The ceramic volume fraction of the composite film was about 0.2.

To reinforce the piezoelectric responses of the PT and copolymer phases, the two phases must be poled in opposite direction [8]. The PT phase of the composite film was first poled by applying a dc field of ~ 65 MV/m at 120°C for 1h. Since the field was applied at a temperature above the Curie temperature of the copolymer, only the PT phase was poled. The copolymer phase was then poled in a direction opposite to that of the PT phase by applying an ac field of frequency 10 Hz and amplitude 70 MV/m at 70°C. The direction of the resultant polarization (remanent polarization) in the copolymer phase was determined by the field direction in the last half cycle of the ac voltage. After poling, the films were peeled off from the glass substrate and the Al electrodes were etched away in potassium hydroxide solution (KOH). Circular elements of diameter about 0.6 mm were cut out from the film for subsequent hydrophone fabrication.

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III. CONSTRUCTION OF THE HYDROPHONE ARRAY

The construction of the 8-element hydrophone array is shown schematically in Fig. 1. Copper wires of diameter 1 mm were held by epoxy in the center of the holes of the polyacetal (POM) housing which was fixed in a stainless steel tubing of diameter 4 mm and length 160 mm. After the epoxy had set, the tips of the copper wires were polished to obtain flat surfaces. The circular elements were glued to the tip of exposed wire using silver-filled conductive epoxy (Ablestik) and the edge of the elements was insulated by epoxy. A Cr/Au layer of thickness 0.15 μm was evaporated onto the top surfaces of elements to make contact with the steel tubing and served as the ground electrode. The center-to-center separation between the elements was 2.5 mm.

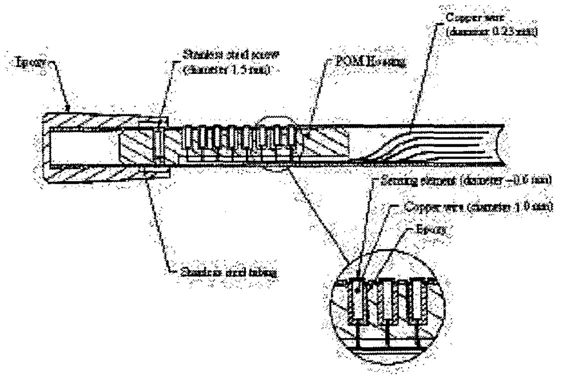

Fig. 1: Schematic diagram of the 8-element hydrophone array.

IV. CHARACTERIZATION OF THE HYDROPHONE ARRAY

(A) Receiving sensitivities of the array elements

Testing of the hydrophone array was carried out in a water tank. A transducer (6.35 mm diameter, Panametrics) was used to generate acoustic waves. The array was placed in the far-field region (distance > a^2/λ, where a is the transducer radius and λ is the wavelength of the acoustic wave) of the transducer to receive the waves. The voltage generated by each array element was measured using an oscilloscope. For comparison, the voltage generated by a standard bilaminar PVDF membrane hydrophone (GEC-Marconi, Type Y-34-3598) located at the same position was recorded. The end-of-cable open circuit sensitivity M_o of the array element was determined by comparing the received voltage from the element with that of the membrane hyrophone.

Table 1 shows the end-of-cable open circuit sensitivities of the array elements as a function of frequency. It can be seen that the sensitivities varied by 3 dB (re 1 V/μPa) in the frequency range of 2 to 8 MHz. The difference in the sensitivities amongst the eight elements was about 7 %.

Table 1: End-of-cable open circuit sensitivities (in μV/Pa) of the array elements at different frequencies

Element	Frequency (MHz)						
	2	3	4	5	6	7	8
1	0.292	0.245	0.241	0.234	0.221	0.214	0.191
2	0.276	0.242	0.243	0.220	0.213	0.208	0.192
3	0.286	0.233	0.231	0.219	0.211	0.208	0.196
4	0.279	0.246	0.232	0.223	0.215	0.207	0.187
5	0.279	0.233	0.227	0.218	0.207	0.203	0.187
6	0.285	0.231	0.240	0.220	0.213	0.208	0.193
7	0.290	0.245	0.236	0.226	0.221	0.208	0.188
8	0.282	0.232	0.236	0.229	0.209	0.208	0.191

(B) Angular responses of the array elements and cross-coupling evaluations

Acoustical and electrical cross-coupling between the array elements can produce undesirable artifacts in the spatial frequency response of an individual element. In the present measurement, a plane transducer was used to generate a short burst of acoustic wave at its center frequency. Two plane transducers (Panametrics) of frequencies 2.25 and 10 MHz were used. The array element positioned on the acoustic axis of the transducer at a point well into the far-field region, and then rotated on an axis through each individual element in two orthogonal directions. The first direction, in which the axis of rotation coincides with the tube axis, measures the angular response of the element in the plane perpendicular to the tube axis. In the other orientation, the axis of rotation was perpendicular to the tube axis and in the plane of the element.

The output voltages of the array elements were measured as a function of incident wave angle θ, and the angular response curves of the elements are plotted in Figs. 2, 3 and 4. The angular responses of the elements perpendicular to the tube axis (Fig. 2) agree closely to the predicted values from the unbaffled piston model [10]. In case of the element rotated in the direction parallel to the tube axis, several dips are observed in the response curves (Figs. 3 and 4). It is because a path difference $\delta = L \sin \theta$ (where L is the inter-element spacing, 2.5 mm) is involved between the signals received by the element under test and its neighboring elements during the rotation. Hence, when the path difference δ is equal to the half a wavelength ($\lambda/2$), the acoustic signal received by the neighboring element is exactly 180° out of phase with the acoustic signal received by the tested element. Through electrical cross-coupling, the output voltage of the tested element decreases due to destructive interference, resulting in formation of the dip. To account for the electrical coupling, a simple theory has been constructed by assuming the coupling amplitude to be of the form $\alpha e^{i\phi}$ (where α is a coupling coefficient and ϕ is a phase shift). The coupling to the n^{th} nearest neighbor then will be $\alpha^n e^{in\phi}$. The angular response is expressed as [11]

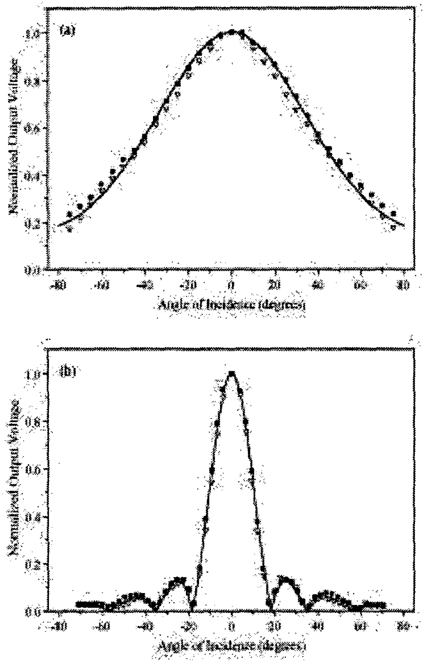

Fig. 2: Angular responses of the array elements in the plane perpendicular to the tube axis at (a) 2.25 and (b) 10 MHz. Experimental values: element 1 (first element from the endcap) with 1 neighbor, ⊞; element 4 (fourth element from the endcap) with 2 neighbors, σ; and theoretical values, ———.

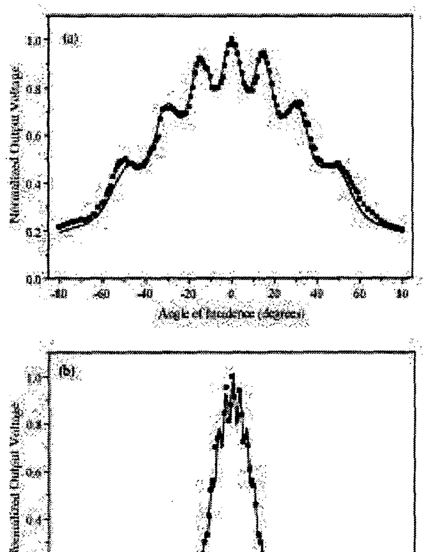

Fig. 3: Angular response of element 1 (first element from the endcap) with 1 neighbor in the plane parallel to the tube axis at (a) 2.25 and (b) 10 MHz. (Experimental values, ⊞; and theoretical values, ———)

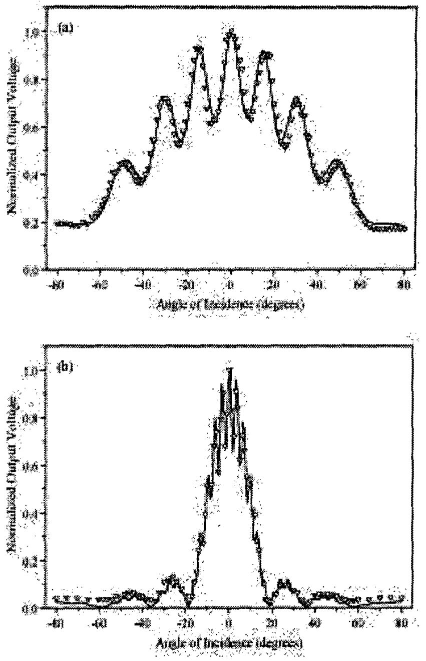

Fig. 4: Angular response of element 4 (fourth element from the endcap) with 2 neighbors in the plane parallel to the tube axis at (a) 2.25 and (b) 10 MHz. (Experimental values, σ; and theoretical values, ———)

$$F(\theta) = V(\theta)\left[1 + 2\sum_{n=0}^{N} \alpha^n e^{in\phi}\cos(nkL\sin\theta)\right] \qquad (1)$$

where k (= $2\pi/\lambda$) is the wave number and N is the number of neighboring element pairs.

In Eq. (1), the first term $V(\theta)$ is the uncoupled response of a single circular element which can be predicted using the unbaffled piston model [10]:

$$V(\theta) = V_0\left(\frac{2J_1(kr\sin\theta)}{kr\sin\theta}\right)\left(\frac{1+\cos\theta}{2}\right) \qquad (2)$$

where V_o is the output voltage when the acoustic wave is normally incident on the element, J_1 is the Bessel function of the first order and r is the radius of the element . The terms in bracket are the modulation due to excitation of neighboring elements. In principle, only the n =1 term is important.

For electrical cross-coupling, the phase shift ϕ is assumed to be zero. Using Eqs. (1) and (2), the theoretical curves were calculated and plotted in Figs. 3 and 4. It can be observed that good agreement is obtained between the measured and the theoretical values with the coupling coefficient α = 0.16. This electrical cross-coupling presumably caused by eight long unsheided wires that bring the acoustic signals from the elements to the impedance matching circuit. However, if the acoustic cross-coupling become significant, time delay involved may lead to nonzero phase shift ϕ, such that more dips may appear at different angles in the response curve. From our measured curves, these additional dips are not observed, indicating that the acoustic cross-coupling among the array elements is not serious.

V. CONCLUSION

An 8-element hydrophone array has been fabricated using 0-3 PT/P(VDF-TrFE) composite film with two phases poled in opposite directions as the sensing element, and its performance has also been evaluated. The array shows good temporal response over several MHz, and the sensitivities of the eight elements are very close. Besides, the array elements have good angular response in the direction perpendicular to the tube axis. However, because of electrical cross-coupling, several dips are obtained in the angular response curves of the elements parallel to the tube axis. To reduce this cross-coupling, a surface mounted impedance matching circuit fitted inside the tube can be used and placed close to each element. With the use of an 8-channel multiplexer, such hydrophone array will be useful to acquire more information at different locations in a much shorter time by measuring the output voltage of each element in turn.

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