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Design Flexural Piezoelectric Acoustic Transducers Array Based d33 Mode Polarization

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ABSTRACT

Piezoelectric Acoustic Transducer (PAT) is a transducers used in many application such as medical diagnostic, medical ultrasonic imaging and underwater acoustic applications. Latest research, PAT were investigated in marine application and underwater acoustic imaging. Conventional PAT is design based on sensing element, Piezoelectric Material, matching layer and backing layer. But the conventional method still has problem with issues of narrow bandwidth, directivity and low sensitivity. This problem is occurred when the transducer need to increase the image resolution. The size of single element will become smaller to meet the requirement of high resolution. PZT-5H have high piezoelectric constant (d31) and low dielectric loss. It is chosen as sensing element in this design of PAT because it will increase the sensitivity of transducers. The PAT is design based on d33 mode polarization to improve the receiving sensitivity. The fabrication process are included wet etching on Printed Circuit Board (PCB), spin coated Polydimethylsiloxane (PDMS), and baked transducer on hot plate. PAT is characterized using Pulse-Echo method. Pulse-Echo method will determine the sensitivity, directivity and operating bandwidth of acoustic transducers in underwater applications. Open circuit receiving voltage (OCRV) is voltage response to determine the sensitivity of acoustic transducer. The commercial projector and hydrophone will calibrate to obtain the reliability of result. In cross talk test, at some particular frequency, Pin 2 and Pin 3 have low sensitivity value. It is because Pin 2 and Pin 3 received low acoustic wave pressure. The PAT array based d33 mode polarization shows it has more receiving sensitive compared to commercial acoustic transducers. The design transducer has sensitivity at -56 dB re 1V/μPa at resonance frequency, 100kHz and fractional bandwidth at 30%.

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1. INTRODUCTION

Piezoelectric Acoustic Transducer (PAT) is transducer used to convert an acoustic signal to voltage signal or vice versa. It is applied in many application such as medical diagnostic [1], [2], medical acoustic imaging [3], [4] and underwater applications [5]-[8]. In conventional piezoelectric acoustic transducer (PAT) design, it is depend on matching layer, piezoelectric material and lastly the backing layer [5], [9]. The operating range frequency is design based on thickness of piezoelectric material and the elastic of membrane's devices [10]. In this situation, PAT is limited in size and the operation bandwidth is narrow. Underwater imaging is required high resolution acoustic transducers to make the image more clear and precise [11]. High resolution image can be obtained with small scale single element and a large number of single element in 2 dimensional.

Piezoelectric Acoustic Transducer is based on piezoelectric material to convert a signal from pressure to electric field or vice versa. Several studies are used Polyvinylidene fluoride (PVDF) [12], [13], Lead Zirconate Titanate (PZT) [14]-[16], Lead Magnesium-Lead Titanate (PMN-PT) [17], Aluminium Nitride (AIN) [18], and Scandium Aluminium Nitride (ScxAl1-xN) [19] as piezoelectric material for particular performance and application. Recently PVDF is used to solve the narrowband issues but it has problem with narrow beam nature [12]. Meanwhile, the PZT-5H is used in application which required high sensitivity. PZT-5H have high piezoelectric constant (d31) and low dielectric loss [16], thus it will induced high displacement sensitivity without dc offset.

A flexural diaphragm are introduced previous papers in paper to increase deformation [20]. In flexural mode transducers array, the bandwidth is maximized by minimizing the pitch, i.e. by maximizing the ratio of the active to total area. The flexural diaphragm can work either in d31 or d33 mode diaphragm. The d33 mode with flexural diaphragm will improved the sensitivity of receiving acoustic transducers [21]. In this paper, the theory of d33 mode polarization is explained in section 2, the design of d33 mode PAT is elaborated detail in section 3, the fabrication of PAT is explained in section 4, the experimental setup of Pulse-Echo method is presented in section 5, the result and discussion is discussed in section 6 and lastly section is the conclusion.

2. THEORY OF d_{33} MODE POLARIZATION

d33 mode polarization in PAT is achieved by polarized piezoelectric material, for example, lead zirconate titanate, PZT-5H as a sensing element is supplied with a DC-voltage and it will induced an electric field. The schematic diagram of d33 mode polarization is shown in Figure 1. If no external pressure on PZT-5H, the polarization is scattered inside PZT-5H material and if an external ultrasonic wave pressure is perpendicularly applied to the membrane, the stresses are induced in PZT-5H.

Refer to Figure 1, the electric field, E, the electric displacement, D, and the polarization vector between positive electrode and negative electrode are parallel to the main planeand along x_3 axis. The stressed in x_3 axis lead to charges in the x3 axis direction, and this will made transducer working in d_{33} mode. The piezoelectricity constitutive equation can be represented in Equation 1.

$$D_3 = d_{33}S_3 \tag{1}$$

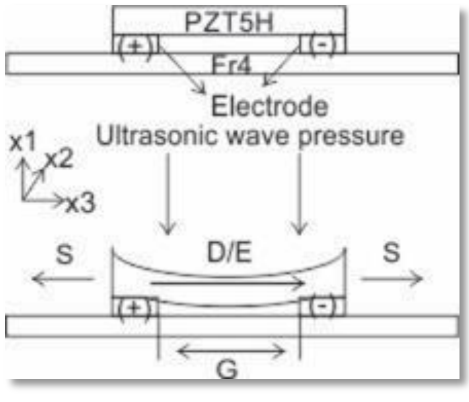


Figure 1. Schematic of d33 mode polarization in PZT5H

The subscript denotes the components in x3 axis, and d33 is the piezoelectric coefficient of piezoelectric material, PZT-5H. If the thickness of PZT-5H is much less compared to distance between electrodes, the electric field, in PZT5H beneath under positive electrodes is almost belong to horizontal components of the electrical displacement, between two electrodes. The capacitance of the two electrodes can be calculated using Gevorgian's model [22], which is complicated and inconvenient. Then the model was simplified and the device capacitance can be calculated as a parallel plate capacitor by introducing an effective area, Ae, which is defined as the equipotential area on which the electric field vectors act perpendicularly. Then the equation for device capacitance can be approximated by

$$C = \varepsilon \frac{A_e}{G} = \varepsilon \frac{W^* l}{G} \quad (2)$$

where ε denotes the permittivity of PZT-5H, Ae denotes the affective area, w is width of electrode, l is length of electrode and G is gap between two electrodes. Then the electric charges, Q induced on electrodes can be obtained from the electric displacement and effective electrode area,

$$Q = D_3 A_e \quad (3)$$

Consequently, the induced voltage is given by

$$V = \frac{Q}{C} = \frac{D_3}{\varepsilon} G \quad (4)$$

Refer to equation 4, it shown that the induced voltage is proportional to the gap between two electrodes, G. Then, thereceiving sensitivity will be referred to the highest voltage produced at a particular frequency.

3. DESIGN d33 MODE PIEZOELECTRIC ACOUSTIC TRANSDUCER ARRAY

The design of d_{33} mode PAT array is shown in Figure 2. The sensing element is piezoelectric material, PZT-5H is adhered on top of printed circuit board (PCB) as shown in Fig 2(b). PCB circuit consists of positive and ground/negative electrodes are arranged in-plane structure on top of FR-4 board. The electrical pad on top of PCB will pull out the electrical voltage from positive electrode to oscilloscope. The polydimethylsiloxane (PDMS) is placed on top of PZT-5H and it will cover the electrical circuit part from conducted with water and functioning as matching layer as well. The parameter of piezoelectric acoustic transducers array is shown in Table 1.

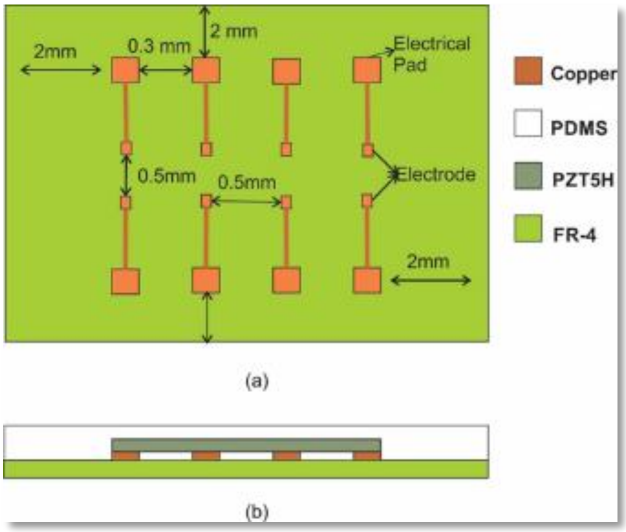


Figure 2. Schematic design of d_{33} mode PMUT, a) top view, b) side view

Table 1. Material Parameter for PAT Array

Material	Parameter		
	Width (mm)	Length (mm)	Thickness (mm)
Copper	0.5	0.5	0.033
PZT5H	1.5	3.5	0.2
PDMS	7	7.5	0.1
FR-4 Board	10	10	1.5875

4. FABRICATION OF d33 MODE PAT ARRAY

Firstly, the electrodes and electrical pad on PCB was fabricated using PCB wet etching process. The PCB after wet etched is shown in Figure 3.

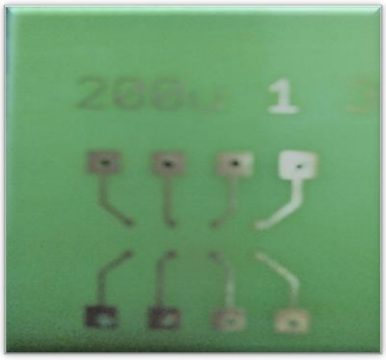
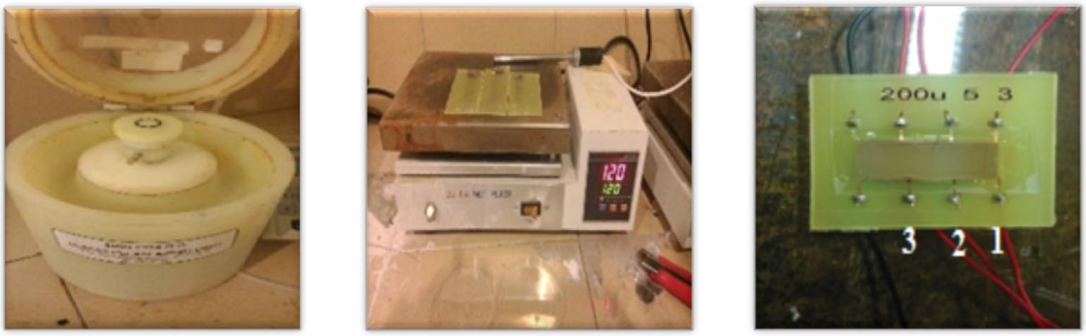


Figure 3. Fabrication Electrodes and Electrical Pad on the Printed Circuit Board (PCB)

Then, take a small spoon of PDMS and placed it on top of electrodes and electrical pad, next placed the PCB on spincoater. And, run the spin coater at 2000 rpm for 60s and 700 rpm for 120s. This process will obtained the thickness of PDMS on PCB board at 50um. Then, used this thickness of PDMS to adhere the PZT-5H with top of PCB. Next, baked the PCB on hot plate with temperature 120°C as shown in Figure 4(b).

This process will take about 1 minute. Then, make it cold about10 minutes. After that took again a spoon of PDMS and placed on top of PZT-5H, and then, placed it on spin coater. The spin coater was set at 1500rpm for 60s and 500 rpm for 300s. The thickness of PDMS on top of PZT-5H will become 100um. Then, the transducer is placed on hot plate. The temperature of hot plate is setup at 120°C and placed it about 20 minute. The fabricated transducer is shows in Figure 4(c).



(a) (b) (c)

Figure 4. a) Spin coater, b) Hot Plate, c) d_{33} Mode Piezoelectric Acoustic Transducers

5. EXPERIMENTAL SETUP

PAT array is measured by pulse-echo experimental method. Pulse-echo experimental method is used to characterize the performance of ultrasonic device in underwater. The sensitivity, resonance frequency and bandwidth can be analysed based on this method. The setup of pulse-echo experimental method is shown in Figure 5.

Test tank with 760 mm × 360 mm × 380 mm size is a place to test PAT in underwater. Function generator (Hameg HM-8150) and pulse forming network (PFN) were worked together to produce a pulse signal. Projector (UNDT-500 kHz, Technotronics Industries, Delhi) was transmitted an acoustic pulse signal in water. PAT was then converted an acoustic signal to electrical signal form. The digital oscilloscope (PicoScope 2204, 10 MHz of Pico Technologies, Inc) was collected data and save it into computer.

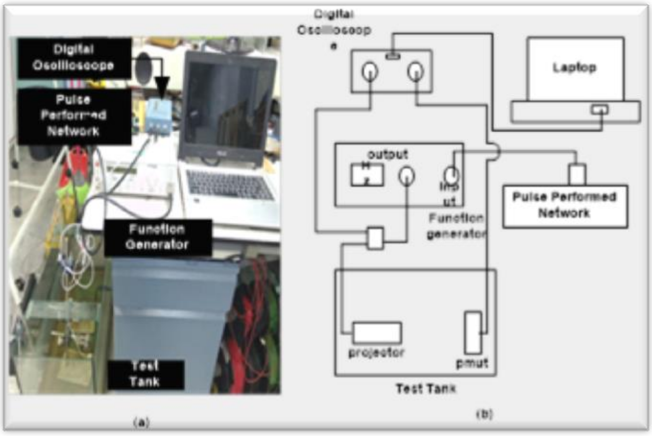


Figure 5. Pulse-Echo Method, a) Experimental Site, b) Schematic Diagram

Three test will be examined which are calibration of commercial projector and hydrophone (UNDT-500 kHz, Technotronics Industries, Delhi), crosstalk test between electrodes and open circuit receiving voltage response. All the results are shown in result and discussion section.

6. RESULT AND DISCUSSION

The calibrations were done on commercial projector and hydrophone to make the data collected are more reliable. The result for 0 mm distance and 40 mm distance are shown in Figure 6. It was shown that for 0 mm distance, there is no gap between the input and output signal.Meanwhile, for 40 mm, there is a small gap between the input and output signal. This is show that the projector and hydrophone is in good condition. The projector and hydrophone will be used to determine the distance between transmitter and receiver.

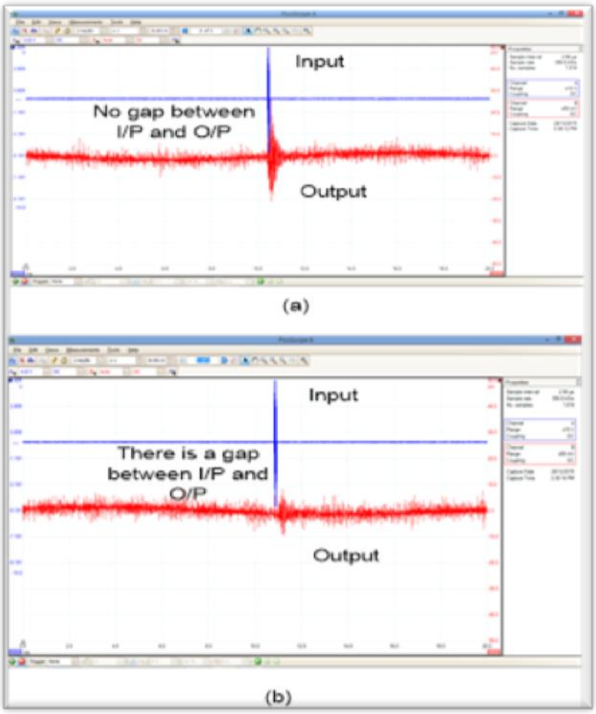


Figure 6. Calibration result for commercial projector and hydrophone (UNDT-500 kHz, Technotronics Industries, Delhi), (a) distance between projector to hydrophone is 0 mm, (b) distance between projector to hydrophone is 40 mm

The sensitivity of receiving transducer is shown in Figure 7. Open circuit receiving voltage response (OCVR) is characterized the Piezoelectric Acoustic Transducers in receiving sensitivity, operation bandwidth and crosstalk. OCVR is measured in dB re V/uPa. OCVR is voltage response obtained at the pressure, 1 uPa. There are small variation measurement value for pin 2 and pin 3 compare to pin 1 at frequency range 100 – 250 kHz and 700 – 850 kHz. There are possibility that cross talk occurred at this particular point frequency. Pin 2 is in between pin 3 and pin 1 as shown in Figure 4(c). Pin 2 has lowest value compared to pin 3 and pin 1 because it received low acoustic pressure wave from projector.

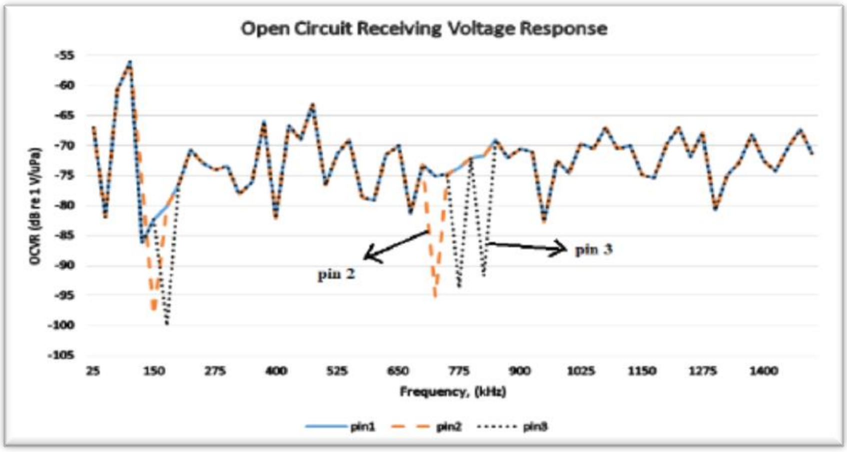


Figure 7. Open circuit receiving voltage for pin 1, pin 2 and pin 3

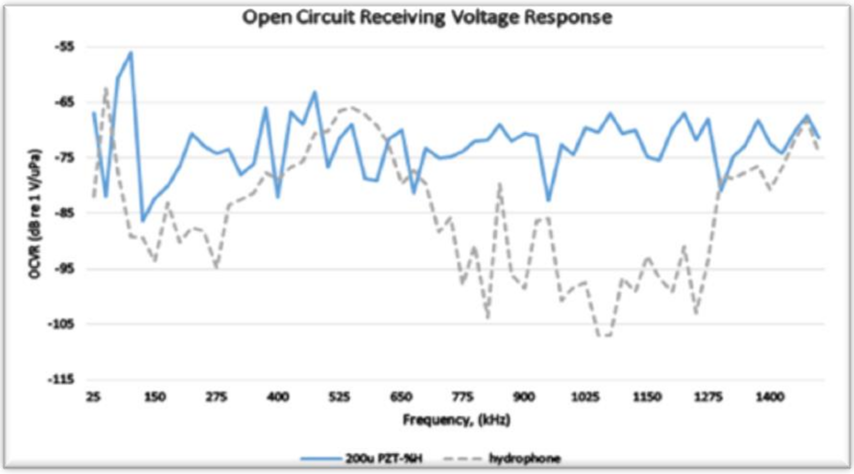


Figure 8. Pulse-Echo Experimental Result

The result shown the PAT array has higher scale in dB compared to commercial hydrophone. The dotted line is shown the result for commercial hydrophone that available in the market. The resonance for PAT array is achieved at frequency 100 kHz, 475 kHz and 850 kHz. PAT array will worked at various frequency from range 100 kHz to 1300 kHz. The receiving sensitivity for PAT is -56 dB re 1V/uPa at 100kHz.

If the transducer is selected working at 850 kHz, so PAT array has a bandwidth of 225 kHz with center frequency at 850 kHz will have fractional bandwidth of 30%. The transducer need to improve in term of operation bandwidth. For future development the transducer will be designed with suitable matching layer and backing layer to improve the operational bandwidth.

7. CONCLUSION

PAT array is successfully designed, fabricated and measured. The fabricated process was started from PCB wet etching, adhered the sensing element, PZT-5H with top of electrodes on PCB and spin coated PDMS layer on top of PZT-5H using spin-coater. PAT array was tested using pulse-echo experimental method. The experiment was successful characterized Piezoelectric Acoustic Transducer in term of receiving sensitivity and operating frequency. The result was shown that at the particular frequency, pin 2 and pin 3 were dropped the receiving value. It was cross talk occurred at particular frequency. In Figure 8, the result was shown that PAT array has more receiving sensitivity compared to conventional hydrophone. The receiving sensitivity achieved by PAT array is -56 dB re 1V/uPa at 100kHz. The fractional bandwidth for PAT is 30%. The operational bandwidth is needed to be improved for future design. It can be improved by designed the PAT array with suitable matching layer and backing layer.

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