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RESEARCH PAPER

Transmitting Performance Simulation of Piezoelectric Transducer for Underwater Application

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Abstract

This paper reports transmitting performance simulation of the circular piezoelectric transducer using finite element analysis (FEA) approach. The 3D model of the transducer is designed and simulated using six different piezoelectric materials. FEA simulation and modelling had been carried out using the COMSOL Multiphysics 5.0 software. The thickness and radius of the piezoelectric material layer were varied and transmitting performance were compared and analysed. From this simulation, the transmitting performance of the Piezoelectric Micro Ultrasonic Transducer (PMUT) is decreased as the membrane radius increased, while it increased as the thickness of the piezoelectric material layer increased. The total device thickness at 430 µm with the membrane radius at 1500 µm, show the best performance at 240 kHz of frequency, tailored for many underwater applications. The thickness and radius have contributed significantly to the mechanical stress generated at the surface of the piezoelectric material layer, in contact with the electrode. Hence, the device radius and thickness of the piezoelectric layer are considered, regardless of the type of piezoelectric material used.

Keywords: piezoelectric, underwater PMUT, simulation, transmitting performance

INTRODUCTION

Ultrasonic transducers are widely used in many underwater applications such as object detection, ranging (Grelowska & Kozaczka, 2014) and velocity measurement and communications (Sadeghpour, Kraft & Puers, 2019). Recent advancement has seen researchers adopt multiple layers using various materials on Piezoelectric Micro Ultrasonic Transducer (PMUT) to achieve desired performance at a specific frequency range. Development cycles that include computer simulations have significantly assisted developers prior to the fabrication phase. However, there is no reported database for a developer to build a transducer mainly in the underwater application, which can be conducted through computer simulation.

A few PMUT studies have been performed so far focusing on underwater applications that relate materials being used with the structural parameters and transmitting performance. Hence, the purpose of this study is to numerically analyse multiple PMUT models using six different piezo-active materials by manipulating its structural parameter to monitor the underwater transmitting performance of PMUT. This study theoretically characterizes the resulting transmitting performance for acoustics pressure and displacement, effected by the changes of thickness of active material layer and radius of the device.

Recently, underwater PMUT with a circular structure was reported using zinc oxide as the active material (Liu, Cheng, Ho, Hung & Chang, 2017). There are a few more examples of PMUT with different materials such as sandwich plate structure using PZT-5A and PZT-5H (Pouladkhan, Foroushani & Mortazavi, 2014), cylindrical PMUT array using aluminium nitride (Shiesh, Sabra & Degertekin, 2018), disc planar using lithium niobate (Chen et al., 2018), and other research using quartz which widely known active material used in Micro Electro-Mechanical System (MEMS). However, these studies only featured a limited comparison of active material for a single structure. Table 1 shows the list of previous work on selected active materials based on the device performances.

Table 1. Previous works of selected active materials

Reference	Active Material	Performance	Remarks
Shieh, Sabra and Degertekin (2018)	Aluminum nitride, Zinc oxide, PZT	Bandwidth improvements nearly 40%	Simulation of a 32-element array with 640 membranes
Chen et al. (2018)	Lithium niobate	Good temperature stability of the electromechanical coupling factors	Potential high-temperature piezoelectric applications
Pouladkahn, Foroushani and Mortazavi (2014)	PZT-5A, PZT-5H, PZT-4	PZT-5H and PZT-5A has the least effect on transverse displacement and Mises stress	Uses ABAQUS 9v.6.7) software to derive FEA on a sandwich plate
Li, Ren, Fan and Wang (2017); Yaacob, Arshad, and A. Manaf (2016) and (2010); Liu et al. (2017)	Zinc oxide, Quartz, PZT	Good sensitivity for hydrophone application	FEA, Simulation and fabrication, underwater sonar
Ahmad, Abdullah and A. Manaf (2017)	PZT-5H	Receiving sensitivity is -66.44 dB re 1V/µPa, Fractional bandwidth is 28% improved	D33 mode electrode in-plane arrangement, Pulse-echo experimental method
Sadeghpour, Pobedinskas, Haenan and Puers (2017)	Aluminum nitride	Reported five resonance frequencies response (100-106 MHz)	Frequency response was measured by LDV, Underwater application

The piezoelectric material has the ability to convert mechanical waves to electrical energy and vice versa. The active material becomes electrically polarized when the membrane is subjected to a strain. The position of atoms was displaced when the membrane deformed, affected by electric dipole throughout the active materials. This effect can be represented in the strain-charge constitutive equation (1),

$$\begin{aligned} S &= s_E T + d^T E \\ D &= dS + \varepsilon_T E \end{aligned} \tag{1}$$

where D is the electric displacement field, T is the stress, E is the electric field, S is the strain, s_E is the material compliance, d is the coupling properties and ε_T is the permittivity of the material. The following stress-charge constitutive equation represents the effect where the material properties $(c_E, e^T, \varepsilon_S)$ have relationships with the parameters (s_E, d, ε_T) as in Equation 2 and 3.

$$\begin{gathered} T = c_E S - e^T E \\ D = dS + \varepsilon_S E \end{gathered} \tag{2}$$

$$\begin{gathered} c_E = s_E^{-1} \\ e^T = d s_E^{-1} \\ \varepsilon_s = \varepsilon_0 \varepsilon_{rT} - d s_E^{-1} d^T \end{gathered} \tag{3}$$

METHODOLOGY

Modelling and Simulation

Basically, a PMUT has multiple layers of the membrane which are composed of top and bottom electrodes and an active layer. Reported that adding a supporting layer at the bottom of PMUT seem essential for a more robust structure (Yaacob, Arshad & A. Manaf, 2010). As shown in Figure 1, a circular 3D modelled PMUT were designed in this work with COMSOL Multiphysics 5.0 software. The layer of silicon dioxide (SiO_2) was designed as supporting layer and both electrodes are composed by copper (Cu).

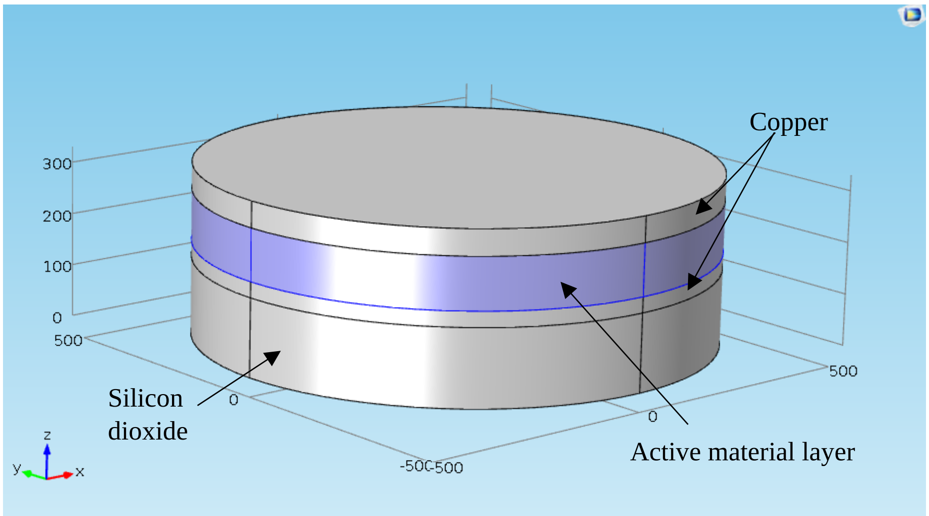


Figure 1. 3D model of PMUT element with first layer and third layer (top and bottom electrode) were composed by copper, second layer with blue region is the active material layer and fourth layer is the silicon dioxide as supporting layer.

This structure was simulated in a water medium setting with six different active materials which were PZT-5A, PZT-5H, aluminium nitride, lithium niobate, quartz, and zinc oxide. The designed structure was modelled referring parameters to the existing PMUT basic structure (Yaacob, Arshad & A. Manaf, 2010; Akasheh, Myers, Fraser, Bose & Bandyopadhyay, 2004; Ahmad, A. Manaf, Yaacob & A. Rahman, 2017) by using finite element method (FEM). Every layer of the basic structure, same dimensions were designed in thickness except for the active material layer. The active materials were analysed with different thickness and diameter for whole structure in every study. All parameters of this selection were determined to be comparable to the existing PMUT basic structure as given in Table 2.

Table 2. Structure parameters of PMUT

	Thickness (μm)	Radius (μm)
Cu (Top)	50	500 - 1500
Active layer*	100 – 200	
Cu (Bottom)	30	
SiO_2	150	

*Active materials – PZT-5A, PZT-5H, aluminium nitride, lithium niobate, quartz, and zinc oxide.

The PMUT model with a fixed 2 V of the applied voltage was analyzed in the structural and electro-acoustic study. In the structural study, the thickness and radius of PMUT were analyzed over the electro-acoustic parameters. In the electro-acoustic study, the frequency of PMUT was analyzed over the structural parameters. The characterizations of transmitting sensitivity were shown in the simulation results. From that, the performances in terms of acoustic pressure and displacement of active material were obtained. Proper mesh analysis was studied including size and type of mesh. In the meshing study, the normal meshing size and tetrahedral meshing structure were selected.

RESULTS AND DISCUSSION

Analysis of acoustic pressure and displacement

Acoustic pressure is used to derive the acoustic intensities. The high resonance frequency and large membrane displacement will benefit the acoustic pressure. Displacement of the membrane is perpendicular to the polarization direction and electric field throughout the piezoelectric material. Higher displacement of the membrane also indicates the greater mechanical stress of the active layer.

In this section, the thickness and radius of PMUT were fixed at 100 μm and 1500 μm, respectively to conduct the frequency study. The comparison of acoustic pressure (Table 3) and displacement (Table 4) between all six materials were recorded against a frequency range between 40 to 240 kHz. The highest acoustic pressure presented in Table 3 is PZT-5H, PZT-5A, and zinc oxide for every frequency level. The acoustic pressure of PZT-5H and PZT-5A was recorded higher by far in value compared to other materials. Meanwhile, the lowest displacement values presented in Table 4 are quartz, lithium niobate and aluminium nitride. Quartz PMUT shows the smallest value of displacement indicates it has the lowest mechanical stress during transmitting.

Table 3. Acoustic pressure comparisons between materials of PMUT

f (kHz)	Acoustic Pressure (PA)					
	Aluminium Nitride	Lithium Niobate	PZT-5A	PZT-5H	Quartz	Zinc Oxide
40	1.08	1.11	43.7	63.8	2.76E-19	1.92
80	4.17	4.29	170	248	6.89E-20	7.43
120	8.89	9.14	362	529	3.06E-20	15.8
160	14.6	15.0	597	871	1.72E-20	26.1
200	20.6	21.1	842	1229	1.10E-20	36.8
240	25.9	26.5	1063	1552	7.66E-21	46.3

Table 4. Displacement comparisons between materials of PMUT

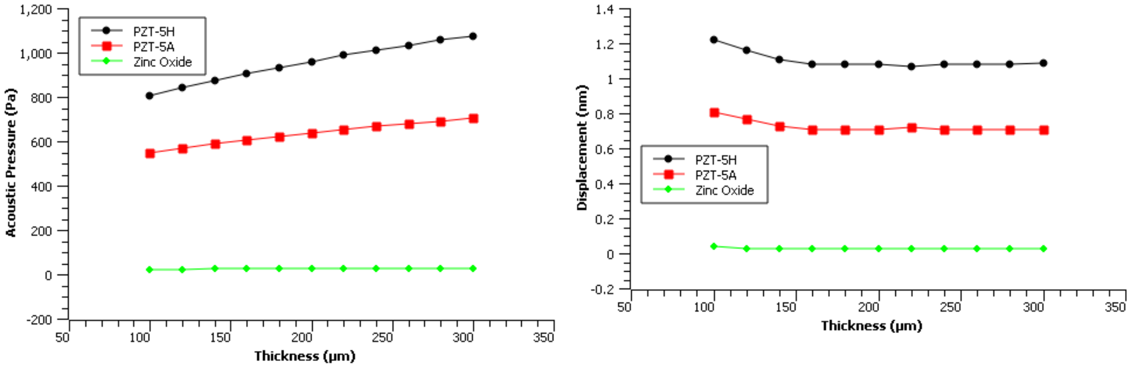
f (kHz)	Displacement (nm)					
	Aluminium Nitride	Lithium Niobate	PZT-5A	PZT-5H	Quartz	Zinc Oxide
40	0.06	0.02	1.68	2.51	3.82E-15	0.08
80	0.06	0.02	1.69	2.52	9.56E-16	0.09
120	0.06	0.02	1.70	2.54	4.25E-16	0.09
160	0.06	0.02	1.72	2.57	2.39E-16	0.09
200	0.06	0.02	1.75	2.61	1.53E-16	0.09
240	0.06	0.02	1.78	2.66	1.06E-16	0.09

From the tables, selected materials were shortlisted to three materials (PZT-5A, PZT-5H, zinc oxide) due to higher possible transmitting performance. The higher the acoustic pressure, the better the transmitting performance. At frequency 240 kHz, acoustic pressure for PZT-5A, PZT-5H, and zinc oxide show the highest values which were 1552 Pa, 1063 Pa, and 46.3 Pa, respectively.

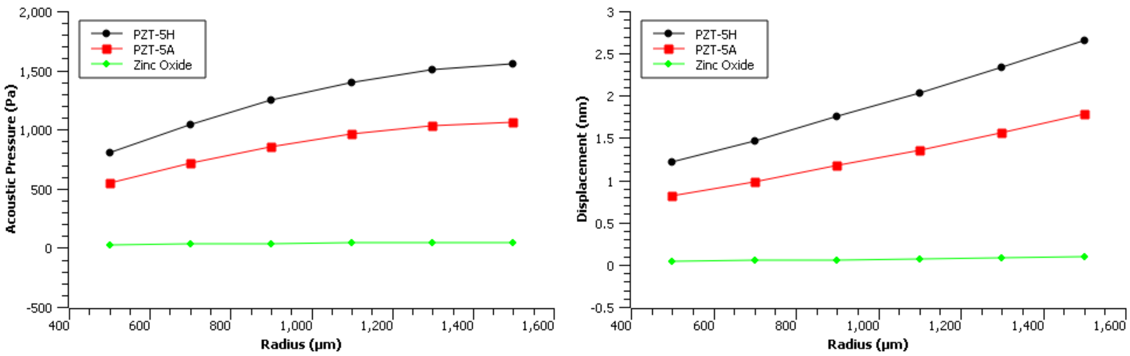
Although the three shortlisted materials show greater value in acoustic pressure, the displacement value for each material was at the highest. The displacement values at 240 kHz for PZT-5H, PZT-5A, and zinc oxide are 2.66 mm, 1.78 mm, and 0.09 mm, respectively. These values show the materials having greater mechanical stress at 240 kHz while transmitting soundwaves. However, those values are significantly smaller compared to the existing PMUT.

Comparison of transmitting performance of PMUT

For this section, the frequency fixed at 240 kHz to compare the diameter and thickness in context of acoustic pressure and displacement of PZT-5H, PZT-5A, and zinc oxide. Figure 2 shows the graph of acoustic pressure and displacement against the thickness of active piezoelectric material and the radius of the PMUT.



(a)



(b)

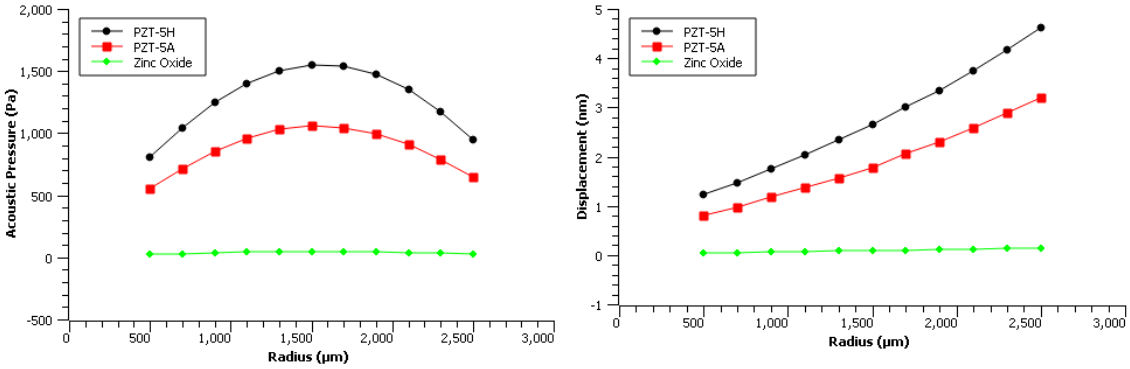
Figure 2. Acoustic pressure and displacement of PMUT were compared between PZT-5H, PZT-5A and zinc oxide at 240 kHz working frequency on (a) thickness and (b) radius of the device.

The transmitting performance of PZT-5H/PZT-5A PMUT was at the best when the displacement is decreasing as increasing of device thickness, while for radius study shows lower transmitting performance since both of acoustic pressure and displacement increasing as the device radius increasing. The best estimated transmitting performance of PZT-5H/PZT-5A was achieved at 240 kHz working frequency, with 1500 µm device radius and 200 µm of active material thickness. While zinc oxide PMUT shows flat line for both radius and thickness study. This actively demonstrates that the obtained transmitting performance for zinc oxide PMUT significantly lower than PZT-5H and PZT-5A PMUT.

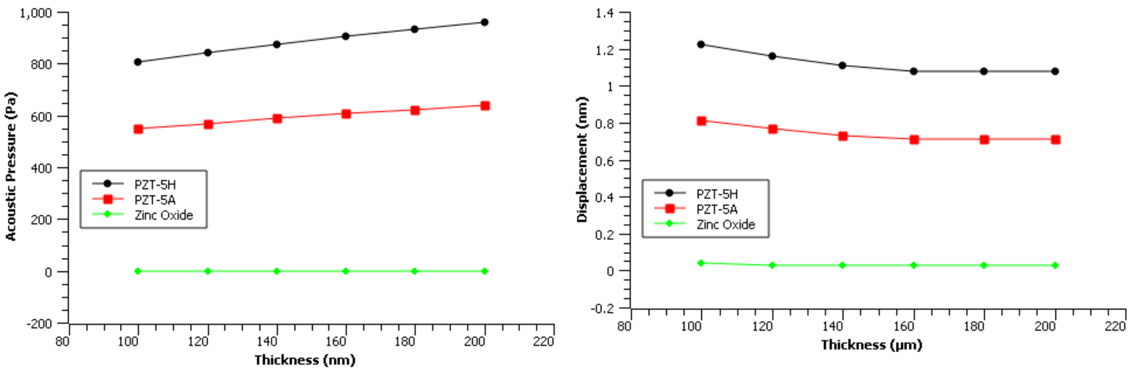
Optimization of radius and thickness of PMUT

The influence of device radius and thickness on transmitting performance were further analysed. Figure 3 shows the relationship between the influence of structural parameter and the transmitting performance.

Figure 3(a) represent the relationship between device radius and the computed acoustic pressure and displacement of PMUT. The displacement shows a negative correlation with device radius, as the values rises when the device radius is increased. However, the acoustic pressure shows the highest value at 1500 µm of radius for PZT-5H and PZT-5A. Lastly the active material thickness shows positive correlation for both acoustic pressure and displacement of PMUT in Figure 3(b). The value of acoustic pressure rises when the device thickness increase, indicates a better transmitting performance. Along the lines of displacement shows a lower mechanical stress of PZT-5H and PZT-5A as the computed values were decreasing. Therefore, the optimal parameters value of PMUT in this work at 240 kHz of frequency are 1500 µm of device radius and 200 µm of device thickness.



(a)



(b)

Figure 3. Acoustic pressure and displacement of PMUT were compared between PZT-5H, PZT-5A and zinc oxide at 240 kHz working frequency on (a) radius of the device and (b) thickness of the active material.

CONCLUSION

Six piezoelectric materials of underwater PMUT were modelled and simulated with the FEM, and the radius of the device and the thickness of active material were further analysed in this study. PZT-5H, PZT-5A, and zinc oxide were selected by testing with frequency study and show the highest performance values at 240 kHz. The transmitting performance of selected active materials were further analysed in thickness and radius study.

In conclusion, the changes of thickness of the active material layer and radius of the device does make an effect on the resultant transmitting performance specifically in acoustics pressure and displacement of PMUT. The physical parameters of a PMUT-based ultrasound sensor combining its work frequency could be optimized efficiently with the proposed numerical method and selection of active materials. It could be useful potentially with guidelines for fabricating a prototype. In additional, it possibly can be the framework for a developer to test the performance of different numerical and parametric for underwater PMUT-based sensor.

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