



The Effect of Material Properties on Sensitivity of the Microelectromechanical Systems Piezoelectric Hydrophone

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ABSTRACT

In this paper, we present mathematical analyses to consider the effect of material properties on the sensitivity of the Microelectromechanical systems (MEMS) piezoelectric hydrophone and improve the sensitivity by choosing the proper material. The selected structure in the present paper is a piezoelectric hydrophone able to work at low frequencies. The piezoelectric hydrophones are widely used in sonar structure. Sonar systems are used in marine vessels and transportation, military submarines, battleships, etc. Piezoelectric hydrophones work by converting the received sound pressure to electrical signals. This conversion of sonar energy to electrical energy is performed by the piezoelectric material in the structure of the hydrophone. Thus, the applied piezoelectric material has significant effect on sensitivity and performance of the sensor. In this paper, the sensitivity of the sensor has been improved from -201.3 dB to -192.6 dB by choosing the proper material with higher piezoelectric coefficients (PZT-2 instead of PZT-5A).

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1. INTRODUCTION

Hydrophone (underwater microphone) receives sound signals under water. In fact, hydrophones receive the pressure of the sound waves and convert it into processable signals in the output. Today, hydrophones are mostly used in low frequencies and the majority of the hydrophone sensors, used in sonar devices, work below 80-kHz frequency [1].

There are several methods to convert sound pressure into electrical signals. Most hydrophones are made of piezoelectric materials, due to their favorable properties. The word 'piezoelectric' is derived from the Greek word piezein, which means 'to press or squeeze'. When a piezoelectric material is under mechanical pressure (whether tension or compression), electric charge appears on its surface. This is due to the asymmetric crystal structure which creates an electric field and electric potential. This phenomenon is called the direct piezoelectric effect. Now, if we encounter mechanical

gravitation and mechanical changes following the application of the electric field, we are dealing with another phenomenon called the inverse piezoelectric effect. Both direct and inverse piezoelectric effects have various applications. In ancient times, in India, crystalline materials such as tourmaline could easily be found. Local people noticed the special property of these materials. When they threw these crystals into hot ashes, they would absorb some of the ashes after a short period of time [2].

This material, which used to be called Ceylon magnet back then, was imported to Europe by a Dutch merchant in 1703. Its electrical effect was discovered by Franz Aepinus in 1756, which was later dubbed the piezoelectric effect in 1824 by Sir David Brewster. The direct piezoelectric effect was discovered by Curie brothers in 1880. They extracted the relations between mechanical force and the output potential to some extent. The inverse piezoelectric effect was discovered a year later, in 1881, by Gabriel Lippmann. He realized that connecting potential to the two opposite sides of a crystal will cause it to change form. This effect was discovered by Curie brothers in the same year, and later,

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examined and tested by other scientists such as Rontgen, Kent, Hewitt, etc. Several materials show the piezoelectric effect, including: natural crystals (sugarcane, quartz, Rachel salt, topaz, Indian peridot), other natural materials (tendons, silk, certain types of wood, enamel, dentin, etc.), synthetic crystals (gallium orthophosphates, langasite, etc.), synthetic ceramics (barium titanium, lead titanate, lead zirconate titanate, etc.), and polymers [3, 4].

In this paper, we design a hydrophone sensor that works at frequencies below 80 kHz and consider the properties of materials for improving its sensitivity by choosing the appropriate materials.

2. PIEZOELECTRIC SENSOR STRUCTURE

Piezoelectric sensors produce an electrical load appropriate to the applied pressure. In order to convert the pressure into processable signals in output, two thin layers of metal are deposited at both sides of the piezoelectric material, forming a capacitor which produces the output signal (voltage) proportionate to the applied pressure. In addition, for working at low frequencies, the piezoelectric layer must be placed on a flexible diaphragm. Thus, there are two materials which are important in sensors: a) the diaphragm material, and b) the piezoelectric material [5]. In fact, a piezoelectric sensor produces a voltage proportionate to the applied pressure (see Figure 1).

3. ANALYZING THE EFFECTIVE FACTORS ON PIEZOELECTRIC SENSOR PERFORMANCE

As mentioned above, the piezoelectric sensors are composed of a movable diaphragm carrying the piezoelectric material. The sensitivity of hydrophone sensors are calculated as follows [6]:

$$S = 10 \log_{10} \left(\frac{V_0}{P_{ref}} \right) \tag{1}$$

where, the reference value is 0 dB related to $V_0/P= 1 \text{ V} / \mu\text{Pa}$. Therefore, the sensitivity of the structures are directly related to the generated voltage. The voltage is generated by the piezoelectric material of the diaphragm and is directly related to the strain of the diaphragm. The strain depends on the composing material of the diaphragm. Therefore, we can increase the sensitivity of the sensor by choosing the proper material of the diaphragm and the piezoelectric. First, we will consider piezoelectric materials.

As mentioned above, the piezoelectric materials have direct and inverse effect (see Figure 2). Both of them have various applications [6].

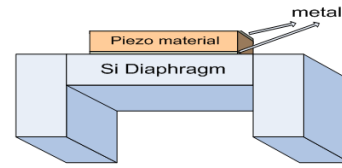


Figure 1. Structure of the piezoelectric sensor

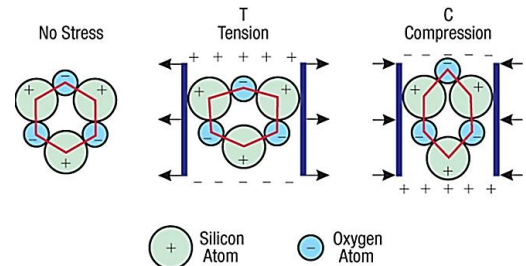


Figure 2. Piezoelectric effect in Quartz under pressure

To express the performances of direct and inverse piezoelectric effects, Equations (2) and (3) can be used, respectively [7]:

$$D = d \cdot \delta + eE \tag{2}$$

$$\varepsilon = d \cdot E + s \delta \tag{3}$$

Which can be expressed in the form of matrices [8]:

$$\begin{bmatrix} D \\ \varepsilon \end{bmatrix} = \begin{bmatrix} e & d \\ d & s \end{bmatrix} \begin{bmatrix} E \\ \delta \end{bmatrix} \tag{4}$$

where, vector D of size (3×1) is the electric displacement (Coulomb/m²), ε is the strain vector (6×1) (dimensionless), E is the applied electric field vector (3×1) (Volt/m) and σ is the stress vector (6×1) (N/m²). The piezoelectric constants are the dielectric permittivity e of size (3×3) (Farad/m), the piezoelectric coefficients d (3×6) or d (6×3) (Coulomb/N or m/Volt), and the elastic compliance s of size (6×6) (m²/N). The piezoelectric coefficient d (m/Volt) defines strain per unit field at constant stress and d (Coulomb/N) defines electric displacement per unit stress at constant electric field.

Among different piezoelectric materials, those which are more asymmetric have more zero elements in their piezoelectric coefficient matrix (d). For example, tetragonal crystals with symmetries of 4 mm have only three elements in their matrices, where indices 1, 2 and 3 represent the axes x , y and z :

$$d = \begin{bmatrix} 0 & 0 & 0 & 0 & d_{15} & 0 \\ 0 & 0 & 0 & d_{15} & 0 & 0 \\ d_{31} & d_{31} & d_{33} & 0 & 0 & 0 \end{bmatrix} \tag{5}$$

The stress matrix, as mentioned, is composed of six components as follows:

$$\delta = \begin{bmatrix} \delta_1 \\ \delta_2 \\ \delta_3 \\ \delta_4 \\ \delta_5 \\ \delta_6 \end{bmatrix} = \begin{bmatrix} \delta_{11} \\ \delta_{22} \\ \delta_{33} \\ \delta_{23} \\ \delta_{31} \\ \delta_{12} \end{bmatrix} \quad (6)$$

where, indices 1-6 represent the generated stress in the x, y, and z axes and in the xy, zx, and zy common axes. Also, for s and e matrices, we have:

$$S = \begin{bmatrix} S_{11} & S_{12} & S_{13} & 0 & 0 & 0 \\ S_{12} & S_{22} & S_{23} & 0 & 0 & 0 \\ S_{13} & S_{23} & S_{33} & 0 & 0 & 0 \\ 0 & 0 & 0 & S_{44} & 0 & 0 \\ 0 & 0 & 0 & 0 & S_{55} & 0 \\ 0 & 0 & 0 & 0 & 0 & S_{66} \end{bmatrix} \quad (7)$$

$$e = \begin{bmatrix} e_{11} & 0 & 0 \\ 0 & e_{22} & 0 \\ 0 & 0 & e_{33} \end{bmatrix} \quad (8)$$

As mentioned above, Equations (2) and (3) are used for sensitivity and mobility of the piezoelectric material, respectively; therefore, we should use Equation (2) in order to examine the sensor. If we rewrite Equation (2) in the form of a matrix in the case of no external applied electrical force, we have:

$$\begin{bmatrix} D_1 \\ D_2 \\ D_3 \end{bmatrix} = \begin{bmatrix} 0 & 0 & 0 & 0 & d_{15} & 0 \\ 0 & 0 & 0 & d_{15} & 0 & 0 \\ d_{31} & d_{31} & d_{33} & 0 & 0 & 0 \end{bmatrix} \cdot \begin{bmatrix} \delta_{11} \\ \delta_{22} \\ \delta_{33} \\ \delta_{23} \\ \delta_{31} \\ \delta_{12} \end{bmatrix} \quad (9)$$

According to Equation (9), the applied stress in the structure can generate an electrical load in the piezoelectric material. This load can be estimated as follows [9]:

$$q = \iint [D_1 \ D_2 \ D_3] \cdot \begin{bmatrix} dA_1 \\ dA_2 \\ dA_3 \end{bmatrix} \quad (10)$$

To calculate the generated voltage, the following equation can be used where c_p is the capacitor formed in the sensor and q is the stored load:

$$V = \frac{q}{C_p} \quad (11)$$

In this paper vertical sound can be received, so for Equation (11) we have:

$$V = \frac{q}{C_p} = \frac{D3A3}{\epsilon_r \cdot \frac{A3}{L}} = \frac{d \cdot \delta}{\frac{\epsilon_r}{L}} = \frac{d}{\epsilon_r} \cdot \delta L \quad (12)$$

Considering the previous equations, the voltage can be calculated as follows:

$$V = g \cdot \delta L \quad (13)$$

where, L is the thickness of the piezoelectric material, σ the stress, and g the piezoelectric coefficient. The relation between d and g is defined as follows:

$$g = \frac{d}{\epsilon_r} \quad (14)$$

where, ϵ_r is the dielectric coefficient in the vertical direction. It can be seen that the piezoelectric coefficient g increases if the piezoelectric coefficient d increases; therefore, we have more output voltage and sensitivity. But, in fact, these factors (d, g) have reverse relationship, because the piezoelectric coefficient d depends on several other factors. For example, for a piezoelectric material with tetragonal crystals and symmetry of 4 mm (such as pzt), the coefficient d_{33} is defined as follows [10]:

$$d_{33} = 2Q_{11}\epsilon_0\epsilon_{33}P_3 \quad (15)$$

where, Q_{11} , P_3 are electrostrictive and polarization factors, and these factors are dependent on the other properties of the material such as Young's modulus, etc. In general, in order to use the piezoelectric material in the direct effect, i.e. converting pressure to voltage, a material with a higher g coefficient must be used. The coefficients for some piezoelectric materials are listed in Table 1.

As mentioned, the voltage generated by the piezoelectric sensors are directly related to the strain (displacement) generated in the sensor as a result of the applied pressure. Therefore, the diaphragm material also plays an important role in the sensitivity of the sensor. Thus, the relationship between diaphragm displacement and the effect of applied pressure and diaphragm material properties must be determined.

TABLE 1. Piezoelectric coefficients for different types of PZT

Compound	d33	d31	d15	g33	g31	g15
PZT-2	152	-60.2	440	38.1	-15.1	50.3
PZT-4	289	-123	496	26.1	-11.1	39.4
PZT-5A	374	-171	584	24.8	-11.4	38.2
PZT-5H	593	-274	741	19.7	-9.1	26.8

We can increase diaphragm displacement by choosing the proper diaphragm material and, then increase the generated stress in the diaphragm and voltage in the piezoelectric material in order to optimize the sensitivity of the sensor. In the present paper, we use the circular diaphragm structure so as to obtain a precise value for the displacement of circular diaphragms, we consider the result of the differential equation of circular diaphragm displacement as follows [11, 12]:

$$\nabla_r^2 \nabla_r^2 w(r) = \frac{d^4 w}{dr^4} + \frac{2}{r} \cdot \frac{d^3 w}{dr^3} - \frac{1}{r^2} \cdot \frac{d^2 w}{dr^2} + \frac{1}{r^3} \cdot \frac{dw}{dr} = \frac{p_z(r)}{D} \tag{16}$$

where, p is the applied pressure, W is diaphragm displacement, r is the radius of the circle, and D is the stiffness of the diaphragm. This equation can be expressed as:

$$D = \frac{Et^3}{12(1-\nu^2)} \tag{17}$$

where, V is Poisson's ratio, t the thickness of the diaphragm, and E Young's modulus for circular diaphragm (see Figure 3).

By solving the above equation and applying boundary conditions, the equation for central displacement of the flat circular diaphragm, is as follows [13]:

$$P = \frac{Et^4}{R^4} \left(\left(\frac{16}{3(1-\nu^2)} \right) \frac{w}{t} + \frac{2.83}{1-\nu^2} \left(\frac{w^3}{t^3} \right) \right) \tag{18}$$

As it can be observed from the above equation, the amount of diaphragm displacement depends on the material and its properties such as Young's modulus (E) and Poisson's ratio (v). The performance of piezoelectric sensors define in a frequency range which is limited by the resonant frequency of the sensor structure. Therefore, we should consider the relationship between resonant frequencies of these sensors. For the resonant frequency of circular diaphragms, using the plate theory and assuming that there is no displacement at the edges of the diaphragm and no aperture in these points, the oscillation frequency of diaphragm can be obtained as follows [14]:

$$f_p = \frac{\alpha_{mn}}{2\pi R^2} \sqrt{\frac{D}{\rho t}} \tag{19}$$

where, ρ is the density of the composing material of the diaphragm, α_{mn} is the constant vibration for the mnth mode of the plate. Constant vibration is different for different modes, e.g. it is 10.21 for the first mode. Now, using the above equations and also simulation with *finite element analysis* (FEA) method, we consider the effect of the composite materials of the sensor.

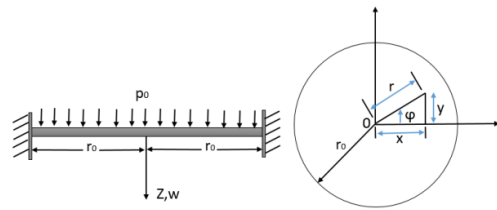


Figure 3. circular diaphragm

4. RESULTS AND DISCUSSIONS

In order to consider the effect of the piezoelectric material on the performance of the piezoelectric hydrophone sensor, first we choose a simple structure of piezoelectric hydrophone sensor for testing the effect of the piezoelectric material. Hydrophone sensors convert the applied sound pressure to a load. In order to convert this load into processable signal in output, thin layers of metal are deposited on both sides of the piezoelectric material. So, by forming a capacitor, it generates the voltage proportionate to the generated load which has been created due to the applied pressure (see Figure 4).

According to the Equation (12), since the generated load and voltage are in the vertical axis (z), therefore d31 and d33 coefficients are important and we should choose material with high d31 and d33 coefficients. First, we design a structure like Figure 5 and then by defining the material PZT-5A for it, we calculate the output voltage based on different pressures (See Figure 6).

As it can be observed from Figure 6, when the pressure increases, the voltage increases in output. In the PZT-5A material, the piezoelectric coefficients are tabulated in Table 2 [15].

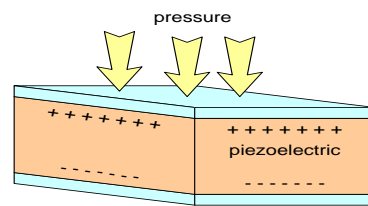


Figure 4. Load generation in the piezoelectric material due to the applied pressure

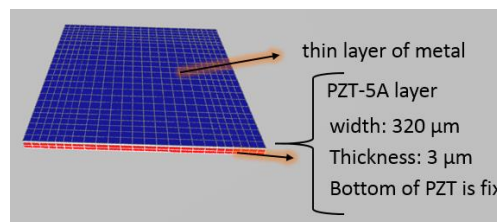


Figure 5. Designed diaphragm to consider the effect of the piezoelectric material

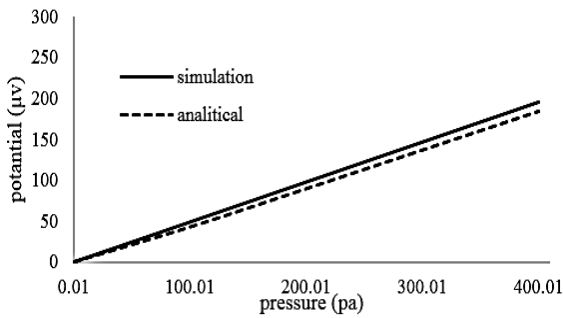


Figure 6. The generated voltage in the piezoelectric material versus pressure

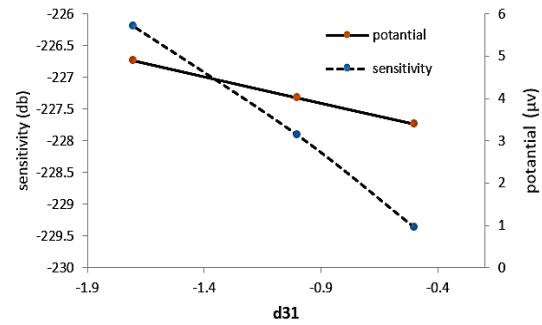


Figure 8. Sensitivity of piezoelectric sensor vs. d31 coefficient

TABLE 2. Piezoelectric coefficients of PZT-5A

$10^{-12}CN^{-1}$	d15	d31	d33
PZT-5A	584	-171	-374

Now, by fixing the value of d31, we change d33 and observe its effect on the output voltage. From piezoelectric equations, it can be seen that by changing d33, the voltage and sensitivity have been changed.

As it can be observed from Figure 7, the sensitivity and generated voltage decrease as d33 coefficient increases. According to equation $g_{33}=d_{33}/\epsilon_{33}$, by increasing d33 the dielectric coefficient increases more than d33. Thus, the voltage and sensitivity also decrease (see equation 13). Now, we consider the effect of the d31 coefficient by assuming that d33 coefficient is constant. The result is illustrated in Figure 8.

As the piezoelectric coefficient $|d_{31}|$ decreases, the voltage and sensitivity are reduced. It is due to fixed d_{33} coefficient that the dielectric coefficient remains constant as well. Since d31 coefficient is decreased, and based on the equation $g_{31}=d_{31}/\epsilon_{33}$, it can be seen that decreasing d31 coefficient causes the piezoelectric coefficient g_{31} to decrease and, as a result, generated voltage is reduced. By decreasing voltage, the sensitivity is reduced.

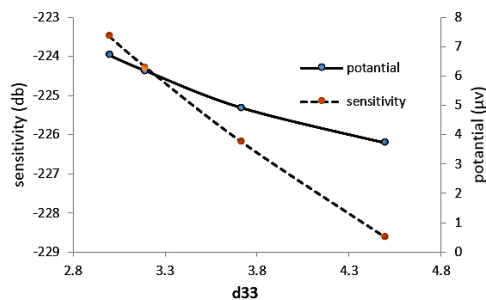


Figure 7. Sensitivity change in the piezoelectric sensor by changing the d33 coefficient

Therefore we can increase the generated voltage by increasing g_{31} and g_{33} coefficients. Thus, by choosing the appropriate piezoelectric material, we can optimize the sensitivity of the piezoelectric sensors. Now, by using proper piezoelectric material, we want to deposit it on an appropriate diaphragm (circular diaphragm with thickness $10 \mu m$ and radius $500 \mu m$) in order to have the best performance at frequencies below 80 kHz. For this purpose, we put a circular diaphragm under a variable pressure of 0.01 to 400 Pascal. The following figure shows the central displacement of the diaphragm versus pressure.

It can be seen from the Figure 9 that as the pressure increases, the displacement of the diaphragm is also increased; this is due to increasing the strain of piezoelectric layer. Thus, to optimize the performance of the sensor in a constant pressure, we have to increase its sensitivity. One of the effective factors is the properties of the diaphragm material. Young's modulus, E, and Poisson's ratio, ν , are the material properties that affect the performance of the diaphragm. The following figures show the effect of these properties on the circular diaphragm displacement at a constant pressure of 10 Pascal.

It can be seen from Figures 10 and 11 that as Young's modulus increases, the displacement and the generated stress and strain at the fixed pressure will decrease, therefore generated voltage and sensitivity are reduced.

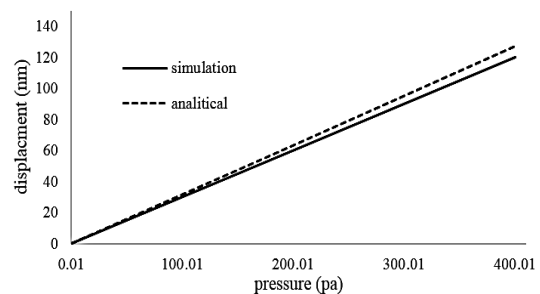


Figure 9. Displacement of the diaphragm versus pressure

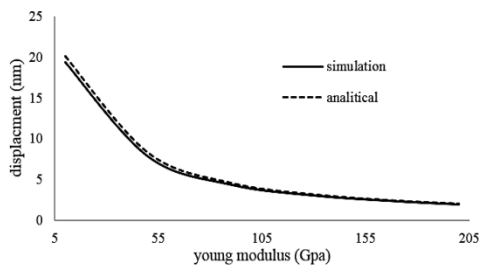


Figure 10. The effect of Young's modulus on the displacement at the pressure of 10 Pascal

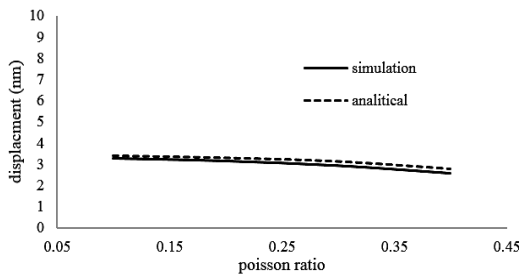


Figure 11. The effect of Poisson ratio on the displacement at the pressure of 10 Pascal

It can also be observed from the Poisson's ratio graph. As Poisson's ratio increases, the displacement decreases, however with a smoother slope compared to that of Young's modulus. This results a decreased generated voltage and sensitivity. Therefore, in order to increase the sensitivity of the sensor, material of the diaphragm must be chosen with small Young's modulus and Poisson's ratio. The effect of the young modulus on the sensor performance, considered in Figure 12.

According to Figure 12, increased Young's modulus leads to decreased displacement and consequently generated voltage. Therefore, the Young's modulus should be minimized. However, as we mentioned earlier, the proper performance of sensor is at frequencies below 80 kHz. Thus, the effect of the material properties which determines the frequency performance of the sensor should be considered. The following figures show the effect of material properties on the resonant frequency of the diaphragm.

Figures 13 and 14 show that when Young modulus and Poisson ratio increase, the resonant frequency rises. Thus, in order to extend the range of frequencies, the Young modulus and Poisson ratio should be increased, but the sensitivity decrease. According to results, it is recommended, that the resonant frequency should be determined by identifying the working frequency range. Then, based on the frequency, the values of Young's modulus and Poisson's ratio should be determined in order to optimize the sensitivity.

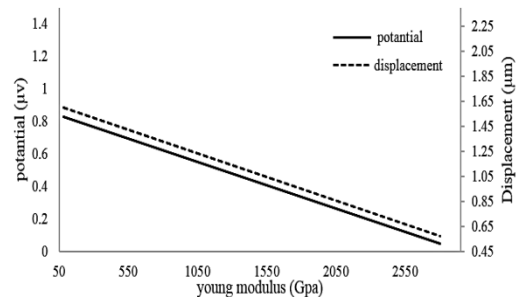


Figure 12. The effect of Young's modulus on displacement and generated voltage

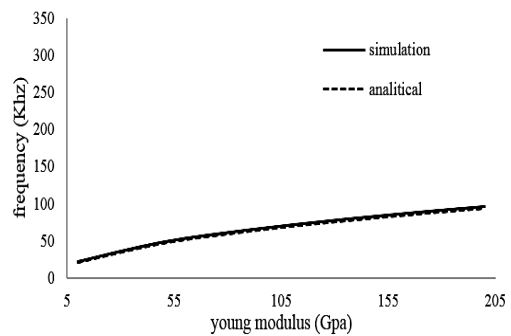


Figure 13. The effect of Young modulus on frequency under pressure of 10 Pascal

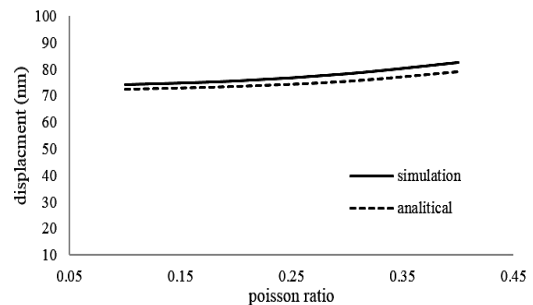


Figure 14. The effect of Poisson ratio on frequency at the pressure of 10 Pascal

Finally, the proper piezoelectric material must be deposited on the diaphragm for the best overall performance of the sensor. In this work, for diaphragm, pzt-2 and SI (Young's modulus=130 Gpa, Poisson's ratio=0.278) are selected (see Figure 15). In the previous structures, the piezoelectric material, PZT-5A, was used [16]. The PZT-2 material can be selected instead of PZT-5A (for increasing g_{31} and g_{33}) to increase the sensitivity of the sensor. In the following figure, the sensitivity of sensor is shown versus frequency. Figure 16 shows that, by changing the piezoelectric material with higher piezoelectric coefficients, the sensitivity has been improved from -201.3 db to -192.6 db.

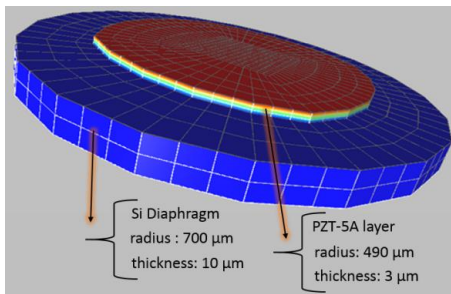


Figure 15. Designed hydrophone structure to consider the piezoelectric material effects on the sensor sensitivity

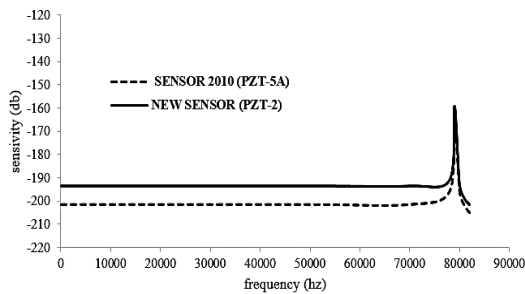


Figure 16. The sensitivity of the hydrophone sensor

5. CONCLUSION

The present paper introduces the materials that can be used in the structure of piezoelectric hydrophones and the effect of the parameters of these materials on the performance of sensor. Using mathematical analysis and simulation, the results show that choosing the proper piezoelectric material and the proper diaphragm material leads to the improvement of the sensitivity of the sensors. In this paper, by changing the piezoelectric material with higher piezoelectric coefficients (PZT-2 instead of PZT-5A), the sensitivity has been improved from -201.3 db for to -192.6 db. The current research, only considered the effect of material properties on the sensitivity of the structure.

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Strain

Sound

در این مقاله به بررسی تاثیر خواص مواد بر روی حساسیت هیدروفن پیزوالکتریک MEMS با استفاده از تحلیل ریاضی و افزایش حساسیت آن با انتخاب ماده مناسب پرداخته شده است. ساختار هیدروفن انتخاب شده در این مقاله یک ساختار پیزوالکتریک با قابلیت عملکرد در فرکانس پایین می باشد. ساختارهای هیدروفن پیزوالکتریک به طور گسترده در سیستم های سونار به کار می روند. سیستم های سونار در زیر دریایی ها، سیستم های حمل و نقل دریایی، ادوات نظامی دریایی و... به منظور شناسایی و مسیر به کار می روند. هیدروفن پیزوالکتریک بر اساس تبدیل فشار صوتی به سیگنال الکتریکی عمل می کند. در حقیقت، ماده پیزوالکتریک به کار رفته در ساختار، فشار صوتی را به انرژی الکتریکی تبدیل می نماید. بنابراین، خواص ماده پیزوالکتریک تاثیر زیادی بر روی حساسیت و عملکرد ساختار دارد. در این مقاله با بررسی و انتخاب ماده پیزوالکتریک مناسب با ضریب پیزوالکتریک بالاتر (ماده PZT-2 بجای PZT-5A) موفق به افزایش حساسیت حسگر هیدروفن پیزوالکتریک از -201.3 db به -192.6 db شده ایم.

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