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Sensitivity Analysis of Mems Based Ultrasonic Transducer by Simulation

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***Abstract:** The development of sophisticated technology sensors became part of our daily life. Sensors are now available which can work even in robust conditions but sensitivity factor is the one that is not allowing them to work in versatile fields of engineering applications. Applications like non-destructive technique, rock crushing, and dangerous gas sensing, and medical imaging require sensors that must be very sensitive and must even detect small changes in the parameter that needs to maintain precise control. Sensitivity factor is majorly influenced by the choice of materials that is considered for manufacturing of these sensors. Sophisticated technology led to development of micro sized sensors for medical field that are used in identification of different parts of fetus using ultrasonic technique. This paper focuses on the choice of composite materials that can be used for MEMS based transducer so as to bring better sensitivity in operation of the device. The present work reports the simulation and analysis of the susceptance results as a function of excitation frequency for the four lowest Eigen frequencies of the structure for different piezoelectric materials under test using COMSOL Multiphysics software.*
Keywords— MEMS, Ultrasonic Transducer, Composite Piezoelectric Material, COMSOL Multiphysics

I. INTRODUCTION

Control has more importance than the Information processing and measuring, it directly interacts with the physical world. Control systems such as sensors and actuators, which help us to make sure that the automation system, can handle activities and environments in desired ways. In 21st Century MEMS has been recognized as one of the most optimistic technology and it has the potential to reorganize both industrial and consumer products by integrating silicon-based microelectronics with micromachining technology [1-3].To interact with the outside such as micro sensors, they usually consist of a central unit that processes data, the microprocessor and several components [7].

To combine mechanical and electrical components, we will create tiny integrated devices or systems, by using a process technology called MEMS. This technique use micro system-based devices that have the potential to dramatically effect of all of our lives and the way we live by providing the miniaturized devices. We can fabricate them in the range from a few micrometers to millimeters, by using integrated circuit (IC) batch processing techniques. These devices have the capability to sense, control and operate on the micro scale, and generate results on the macro scale. Because of its potential applications like non-destructive testing (NDT), welding machining, cleaning, underwater communication, navigation, map building, ultrasonic surgery, Ultrasonic transducers demand has increased in the recent past. Due to its high frequency range from 20kHz to 200kHz and features like high acoustic efficiency, mechanical flexibility, low mechanical Q, low cross talk and low acoustic impedance sonic, ultrasonic and mega sonic, ultrasonic transducers are used in wide range of applications. In ultrasonic measurement system, ultrasonic transducer plays an important role in generating and receiving an ultrasound, this sensor works generally by emitting a short burst of 30 kHz from a piezoelectric transducer. These electromechanical devices are complex and are difficult to Characterize and design, because the sensitivity and resolution of the device entirely depend upon the piezocomposite materials being used. In market the devices which are built by using lead metaniobate piezo ceramic or piezoelectric polymers and producing high resolutions are available. The drawbacks of these devices are showing low sensitivity as most of the acoustic energy is absorbed in the backing and materials efficiency is lowered. To analyze these transducers is difficult for us because, these transducers involve both the combination of electrical and mechanical components. To produce better results than the conventional piezoelectric devices we need to design, which combines a Piezoelectric ceramic and a passive polymer to get a Piezo composite [10].

Hence, here we will mainly concentrate on design of composite piezoelectric ultrasonic transducer for different piezoelectric materials and computation of susceptance as a function of excitation frequency for the proposed structure.

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II. THEORETICAL BACKGROUND

The composite transducer works based on the phenomenon of piezoelectric effect, to generate and measure the ultrasonic pulses. Piezoelectric effect in the transducers is generated by two main materials called piezoelectric ceramics and single crystals. Lead zirconate titanate (PZT) is the most Common piezoelectric ceramic used today along with other materials like sodium tungstates, lithium tantalite, lead titanate, zinc oxide, barium titanate and barium strontium titanate.

Magnesium niobate-lead titanate, which is a single crystal material along with gallium phosphate, quartz and tourmaline, is also used in manufacturing of these transducers [3-6]. Because of the flexibility provided by the crystals in designing, we will achieve different vibration modes by made them into various shapes. This helps the transducer in operating from low kHz range up to the MHz range. When we apply the voltage across certain surfaces of a solid then it undergoes a mechanical distortion, which exhibits the piezoelectric effect. Conversely when mechanical stress is applied between surfaces of a solid dielectric it generates piezoelectric effect. The combined effect of the electrical behavior of the material is piezoelectricity i.e.,

$$D = \varepsilon E$$

Where D = electric displacement, ε = permittivity and E = electric field strength. The Stress charge form of equations is as follows

$$T = C_E * S - e^t * E$$
$$D = e * S + \varepsilon_S * E$$

Where S = stress, e^t = permittivity at constant strain, T = stress. The crystals will bend in different ways in different frequencies when we apply the Stress, but the resonating frequency range will be narrow. The Transducers which produces an electrical output from a mechanical input, uses piezoelectric materials are phonograph cartridges, microphones, and strain gauges. But in earphones and ultrasonic transmitters we can observe the mechanical output from an electrical input. Piezoelectric transducers are best suited for harsh environments, because they are less expensive, whereas electrostatic transducers have very high initial cost and very low system resistance.

III. MODEL DESIGN IN COMSOL MULTIPHYSICS

Piezo electric transducers are designed by defining parameters for the required geometry, selection of necessary material and addition of physical interfaces [7-9]. Certain instructions must be followed for modelling. Initially piezo electric devices (pzd) are selected and then Eigen frequency analysis was chosen. First circle with radius 27.5e-3m was chosen for required shape. Then, Bezier polygon is chosen and its segments are located in the control point sub section by adding the value of x in row 2 for about 0.03 and then add linear button.

This Structure is converted to solid by rotating it about 10 degrees. We use the structural symmetry by cutting along its mid plane which is perpendicular to central axis, to reduce memory requirements. The final 3-D model can be obtained after cutting the geometry, and by locating the points from the work plane as shown in Fig. 1. The mesh can be generated in Fig. 2 by defining the variables for the susceptance so the compensating factors, symmetry and degree of wedge is taken into consideration.

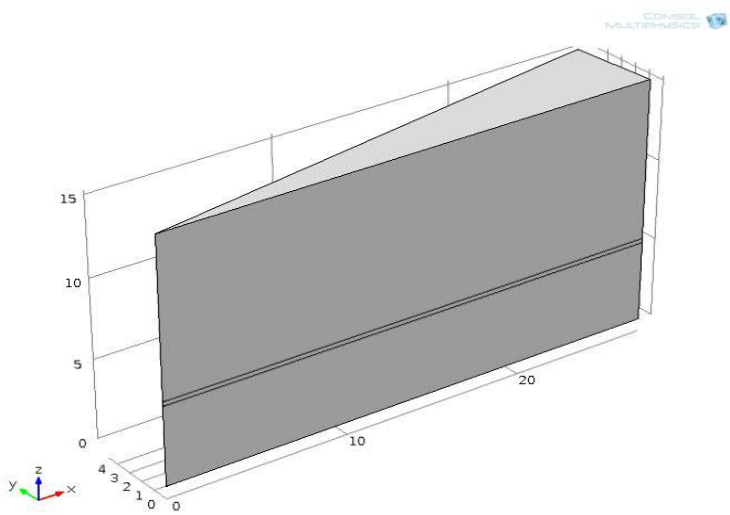

Fig. 1. 3-D view of model geometry of Composite Piezoelectric Ultrasonic Transducer.

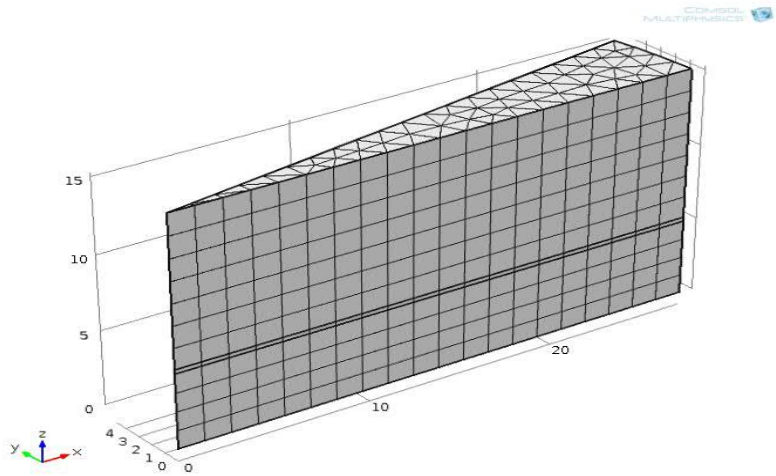

Fig. 2. Generation of mesh for model geometry.

The composite piezoelectric ultrasonic device has a cylindrical geometry. This model consists of a piezoceramic (NEPEC 6) and two Langevin type transducers in which a disk is sandwiched between a pair of aluminium disks by means of adhesive (ARALDITE) i.e., the layers are organized as follows aluminium layer-adhesive layer-piezoceramic layer-adhesive layer-aluminium layer Fig 3,4,5, 6 and 7 [11]. During the modelling of the geometry, domains must be selected so that the required material can be inserted in the proper area and they are as follows

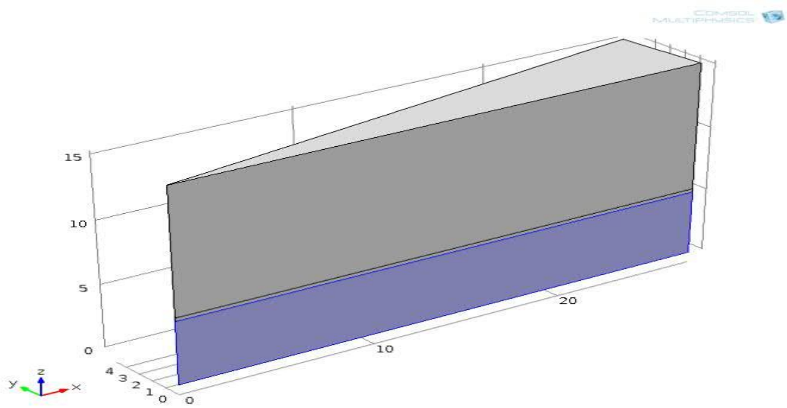

Fig. 3 Piezoelectric material in domain 1

TABLE I
PHYSICAL PROPERTIES OF NEPEC 6 MATERIAL

S. No	Property	Name	Value
1	Young's modulus	E	e={15.7-6.1-6.10} (C/m^2)
2	Poisson's ratio	nu	0.32
3	Density	rho	7730

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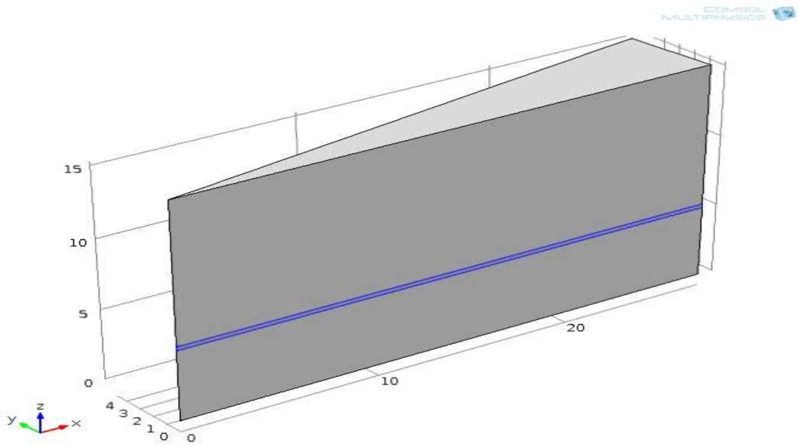

Fig. 4 Adhesive material in domain 2

TABLE II
PHYSICAL PROPERTIES OF ADHESIVE MATERIAL

S. No	Property	Name	Value
1	Young's modulus	E	$1e^{10}$
2	Poisson's ratio	Nu	0.38
3	Density	Rho	1700

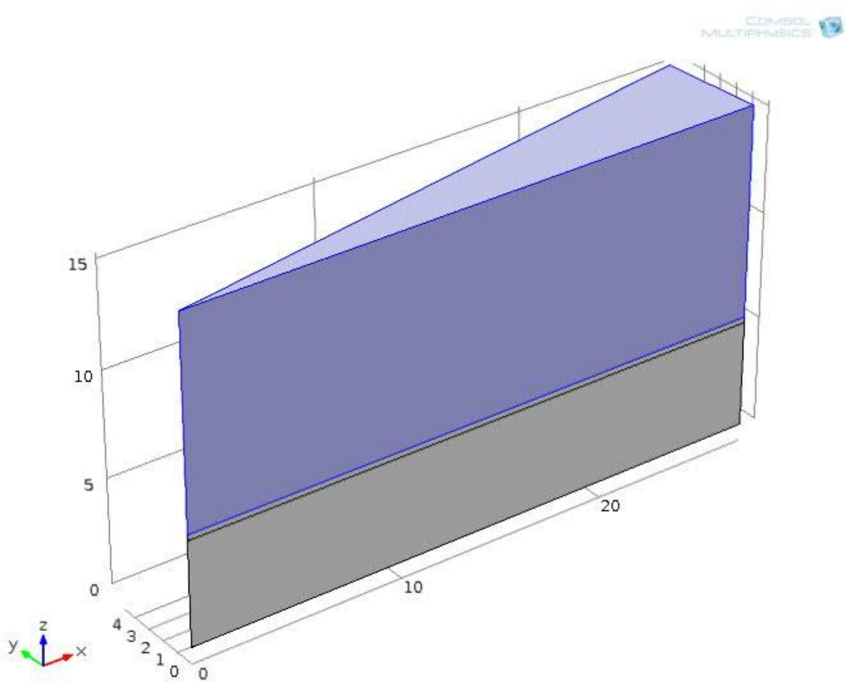

Fig. 5 Aluminum in domain 3

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TABLE III
PHYSICAL PROPERTIES OF ALUMINUM MATERIAL

S. No	Property	Name	Value
1	Young's modulus	E	$7.03e^{10}$
2	Poisson's ratio	nu	0.345
3	Density	rho	2690

Because of its design flexibility by choosing material combinations and dimensions [12], this type of construction is used for sonar transducers and is of practical importance.

The most popular choice for medical ultrasonic transducer is one of the piezoceramic materials, lead zirconate titanate. The pzt-8 is prominent in selection during the construction of medical transducers, because it offers high electromechanical coupling a wide selection of dielectric constants. The below Table I, II, and III shows the material constants used during the design of transducer

A. Input Parameters

The suspectance for the geomentry is calculated by selecting the boundary conditions for the terminal, ground and symmetry position so that the input parameters can be applied.

The application of the potential for about half of the total peak value i.e., 0.5 volts, because here as we are modelling only for the upper part of the transducer. The ground is selected to be boundary 3 from the electrical boundary conditions of software. Where Electrical terminal is selected in boundary 6 so that the voltage can be applied to it form terminal type. By selecting the boundaries in the model from 1-5, 7, and 8 we get the condition for satisfying the symmetry. This condition cab be expressed by the following equations,

1). Terminal $\int \partial\Omega \rho s ds = Q0$.

2). Ground V = 0.

3). Symmetry n.u = 0.

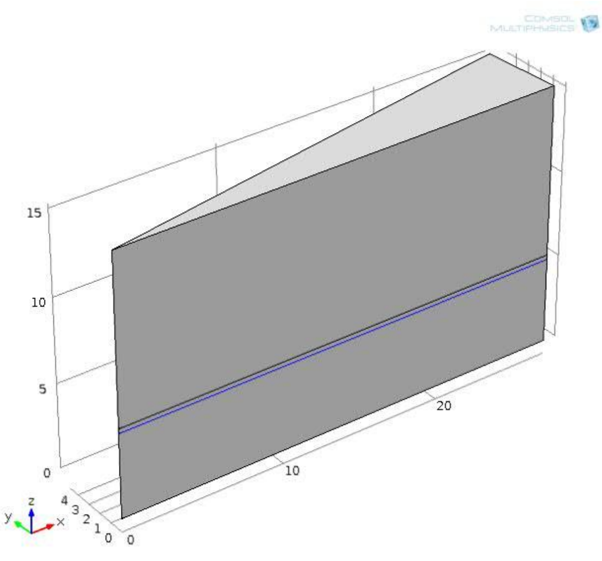

Fig. 6 Terminal in geometry

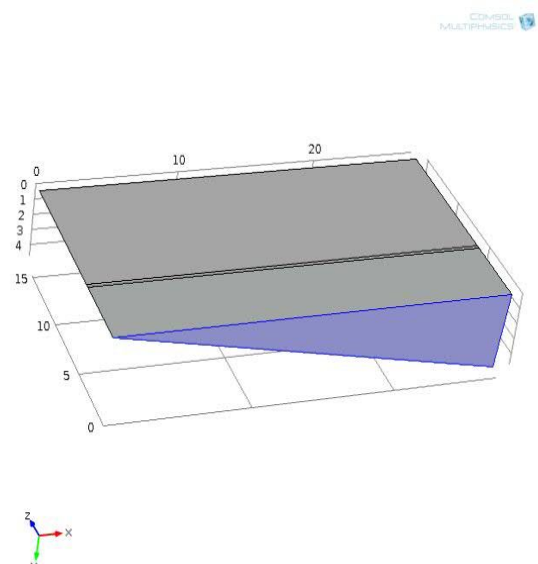

Fig. 7 Ground in geometry

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Linear elastic material model is used here for which equation is given by C = C (E, V), in which E represents young's modulus and V for Poisson's ratio.

IV. SIMULATION

In this study, the simulations are performed using the Piezoelectric Devices module under the MEMS model in COMSOL Multiphysics, which is designed specifically to support the numerical modulation of Eigen frequencies of the composite transducer [11]. Simulation comprises of first meshing the geometry as shown in Fig 2 and then calculation of lowest Eigen modes are calculated by replacing the expression of displacement field and the other one involves the application of the frequency swept. Deformations are observed after the expression is replaced to susceptance. Since we applied AC potential between the electrical terminals on both sides of the electrode surface, the imaginary part of the admittance i.e., susceptance is calculated. This can be computed by knowing the ratio of total current applied and voltage supplied for the given structure. Where the maximum allowed potential is one volt peak for the first four lowest eigen frequency.

V. RESULTS AND DISCUSSION

sing COMSOL Multiphysics software, two kinds of studies has been explored i.e., study 1 is for calculation of the lowest eigen modes. The lowest vibration Eigen mode of the transducer for Barium Sodium Niobate, Gallium Arsenide, Lithium Niobate, Cadmium Sulfide materials are shown in Fig 8, 12, 16 and 20 respectively. Whereas the study 2 corresponds to the frequency domain case in which frequency swept is noted down for the first four Eigen frequencies. The range of the frequency is given form $20e^3$ to$106e^3$ and for a step about $2e^3$ deformation is observed by plotting on the material. Now the displacement field, Z component is selected form the solid mechanics of piezoelectric devices by replacing the expression of surface 1. Electrical potential and slices of deformations are observed by plotting the surface 1 for four different materials [10], which are shown in Fig 10, 14, 18 and 22 for four materials respectively. Total displacement can be observed for the model, after the application of the frequency swept. Later slices are formed for the model which helps in analyzing the internal deformation. 1- Dimensional graph is obtained by replacing the expression to susceptance for the vertex one, which shows the relation between the susceptance and frequency. 1D plot shown in Fig 11, 15, 19 and 23 corresponds to the relation of susceptance versus frequency for Barium Sodium Niobate, Gallium Arsenide, Lithium Niobate, Cadmium Sulfide materials respectively.

The first material considered for analysis was Barium Sodium Niobate, followed by Gallium Arsenide, Lithium Niobate, Lithium Tantalite materials respectively for which maximum and minimum displacement values are tabulated in table IV. The maximum and minimum values of the total displacement for individual materials after application of the frequency swept can be observed from table V. whereas the values of susceptance, both the maximum and minimum for different material under test can be observed from table VI.

TABLE IV
SURFACE DISPLACEMENT VALUES FOR LOWEST EIGEN MODES

Material	Maximum value	Minimum value
Barium Sodium Niobate	2.8477×10^{-4}	0
Gallium Arsenide	2.7895×10^{-5}	-7.7255×10^{-4}
Lithium Niobate	2.8869×10^{-5}	0
Cadmium Sulfide	4.3963×10^{-5}	-4.3395×10^{-6}

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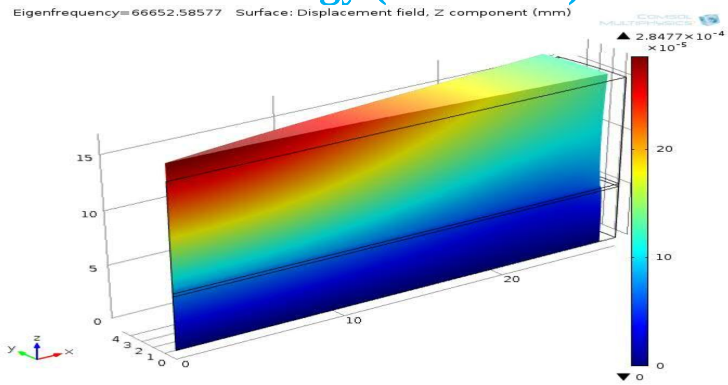

Fig. 8. The lowest vibration eigenmode of the transducer for Barium Sodium Niobate material

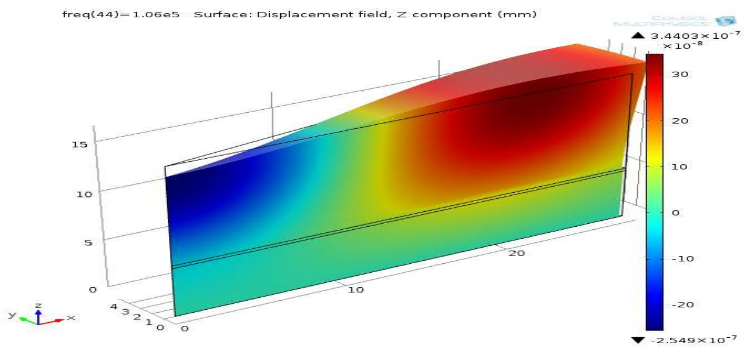

Fig. 9. Surface displacement as a function of frequency swept for Barium Sodium Niobate material

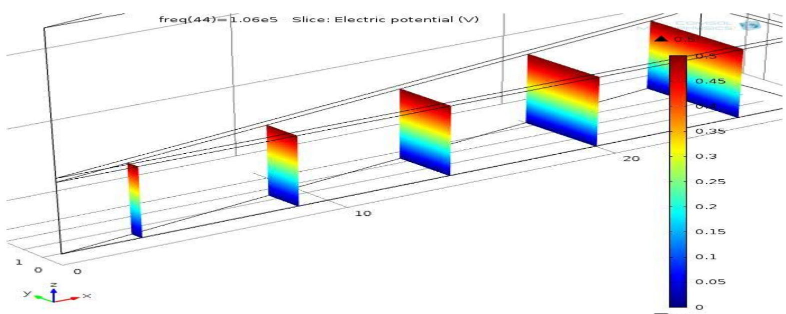

Fig. 10. Electrical potential slices for frequency sweep for Barium Sodium Niobate material

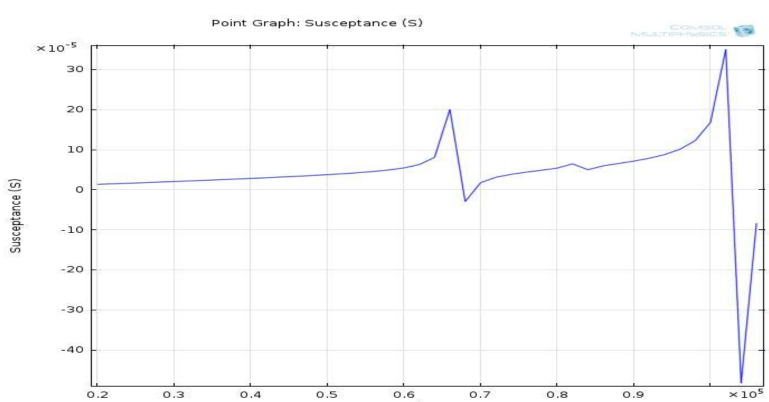

Fig. 11. Input susceptance as a function of excitation frequency for Barium Sodium Niobate material

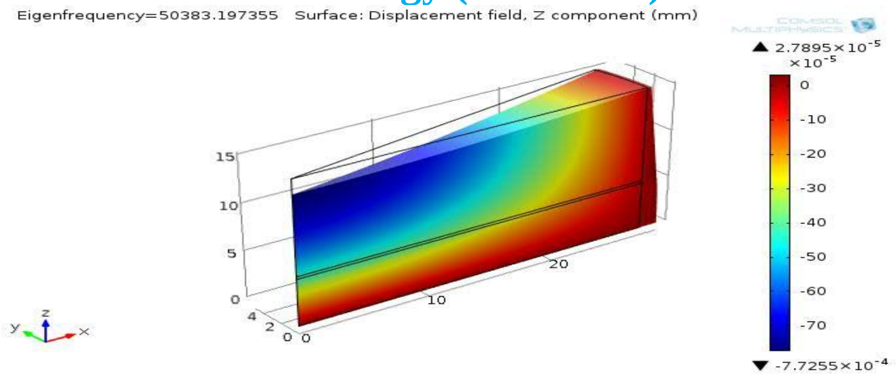

Fig. 12 The lowest vibration Eigen mode of the transducer for Gallium Arsenide material

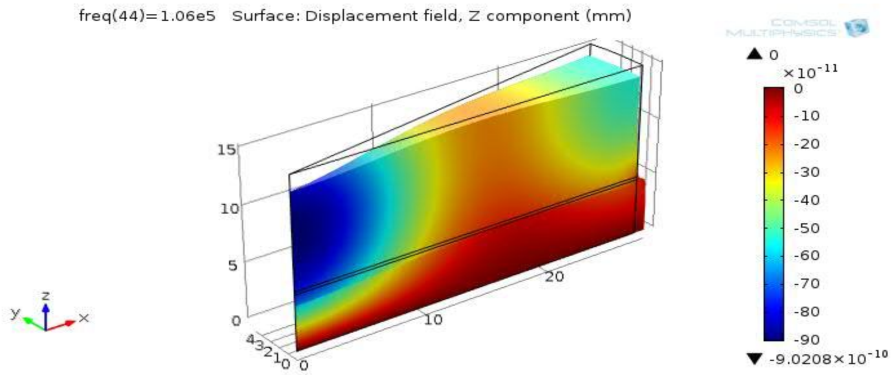

Fig. 13 Surface displacement as a function of frequency swept for Gallium Arsenide material

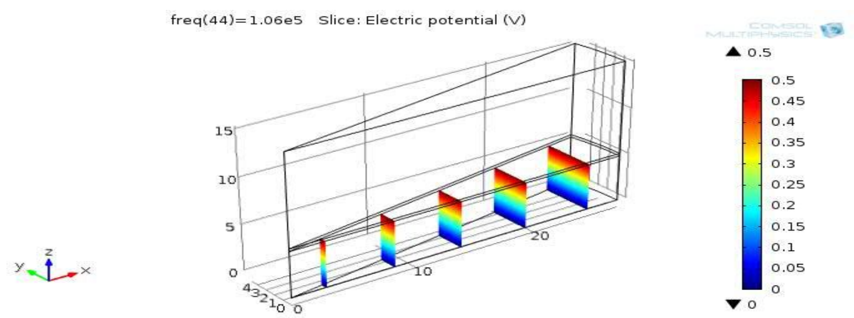

Fig. 14 Electrical potential slices for frequency sweep for Gallium Arsenide material

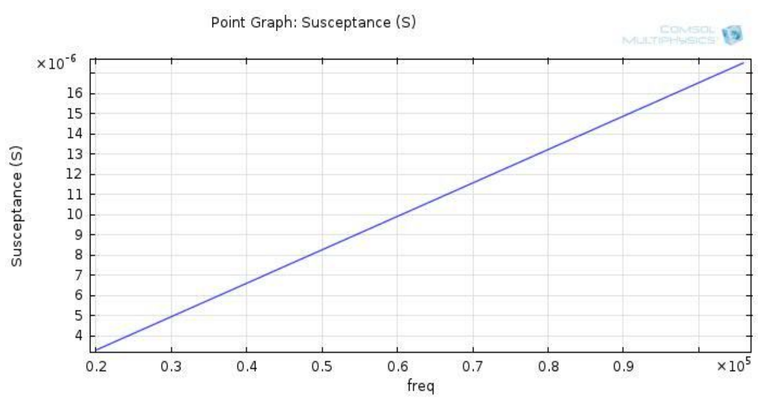

Fig. 15 Input susceptance as a function of excitation frequency for Gallium Arsenide material

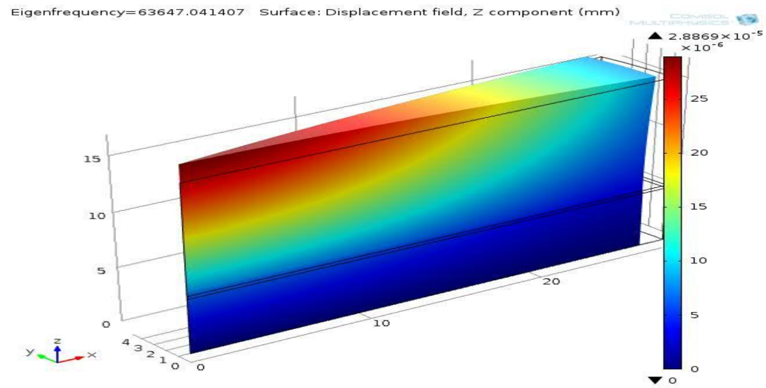

Fig. 16 The lowest vibration eigenmode of the transducer for Lithium Niobate material

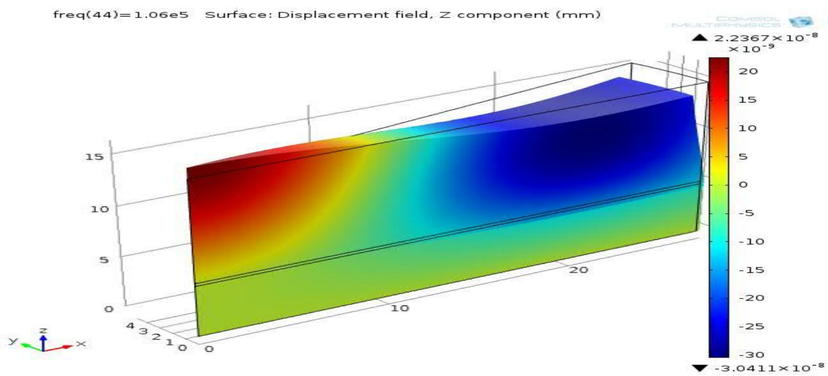

Fig. 17 Surface displacement as a function of frequency swept for Lithium Niobate material

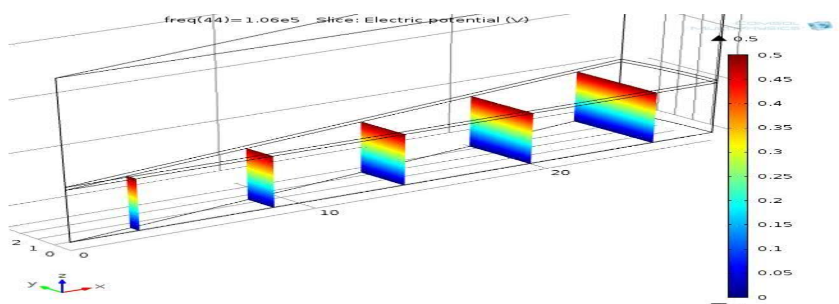

Fig. 18 Electrical potential slices for frequency sweep for Lithium Niobate material

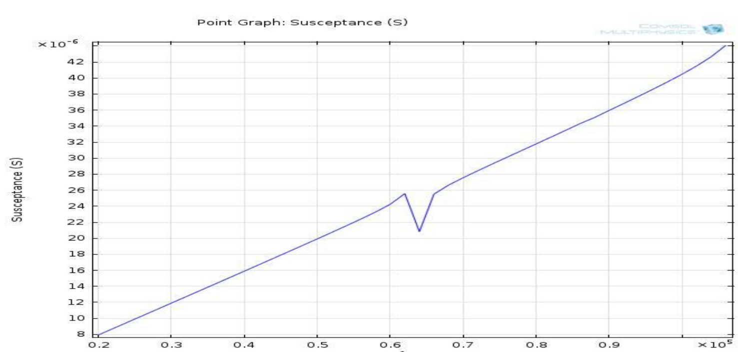

Fig. 19 Input susceptance as a function of excitation frequency for Lithium Niobate material

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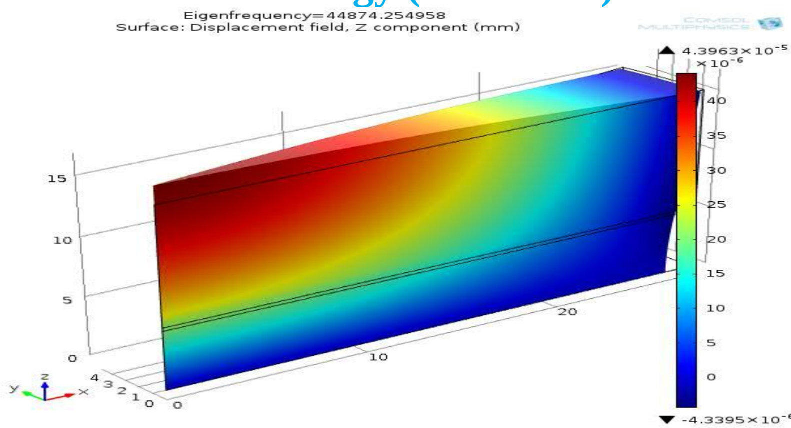

Fig. 20 The lowest vibration eigenmode of the transducer for Cadmium Sulfide material

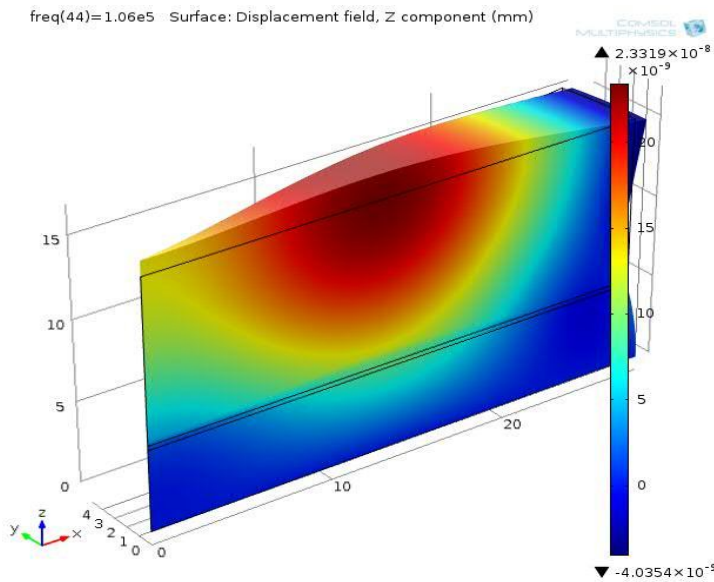

Fig. 21 Surface displacement as a function of frequency swept for Cadmium Sulfide material

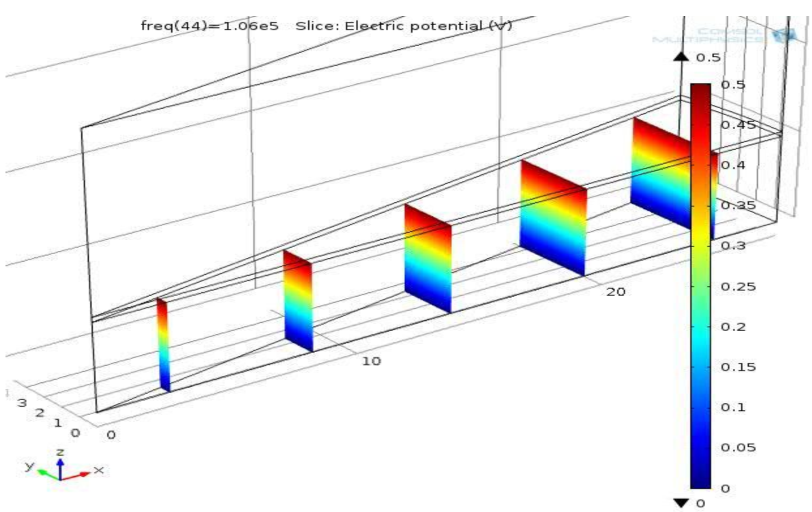

Fig. 22 Electrical potential slices for frequency sweep for Cadmium Sulfide material

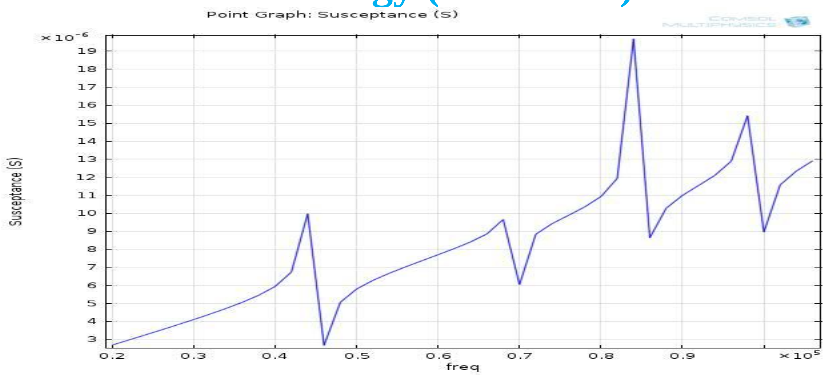

Fig. 23 Input susceptance as a function of excitation frequency for Cadmium Sulfide material

TABLE V
SURFACE DISPLACEMENT VALUES FOR FREQUENCY SWEPT

Material	Maximum value	Minimum value
Barium Sodium Niobate	$3.4403x10^{-7}$	$-2.549x10^{-7}$
Gallium Arsenide	0	$-9.0208x10^{-10}$
Lithium Niobate	$2.2367x10^{-8}$	$-3.0411x10^{-8}$
Cadmium Sulfide	$2.6216x10^{-8}$	$-3.5528x10^{-8}$

TABLE VI
SUCEPTANCE VALUES FOR DIFFERENT MATERIALS

Material	Maximum value	Minimum value
Barium Sodium Niobate	$34x10^{-5}$	$-40x10^{-5}$
Gallium Arsenide	$17x10^{-6}$	$3x10^{-6}$
Lithium Niobate	$44x10^{-6}$	$8x10^{-6}$
Cadmium Sulfide	$2x10^{-6}$	$20x10^{-6}$

VI. CONCLUSION

MEMS based composite piezoelectric transducer model is designed using COMSOL Multiphysics software for different piezoelectric materials. These results seem to suggest that it is advantageous in using cadmium sulfide over gallium arsenide or PZT materials that are used widely. These results help in better choice of piezoelectric material for ultrasonic transducer manufacturing. As this sensor is widely used for detection of fetus images in medical imaging technique when fabricated using cadmium sulfide there are more chances for the ultrasonic amplification due to non-linearity electron lattice interaction and as it gotten different dielectric constants it finally helps the medical transducers as the major material. Finally piezoelectric material characteristics affect the significance behavior of transducer so to achieve better sensitivity proper composite piezoelectric material combinations must be considered.

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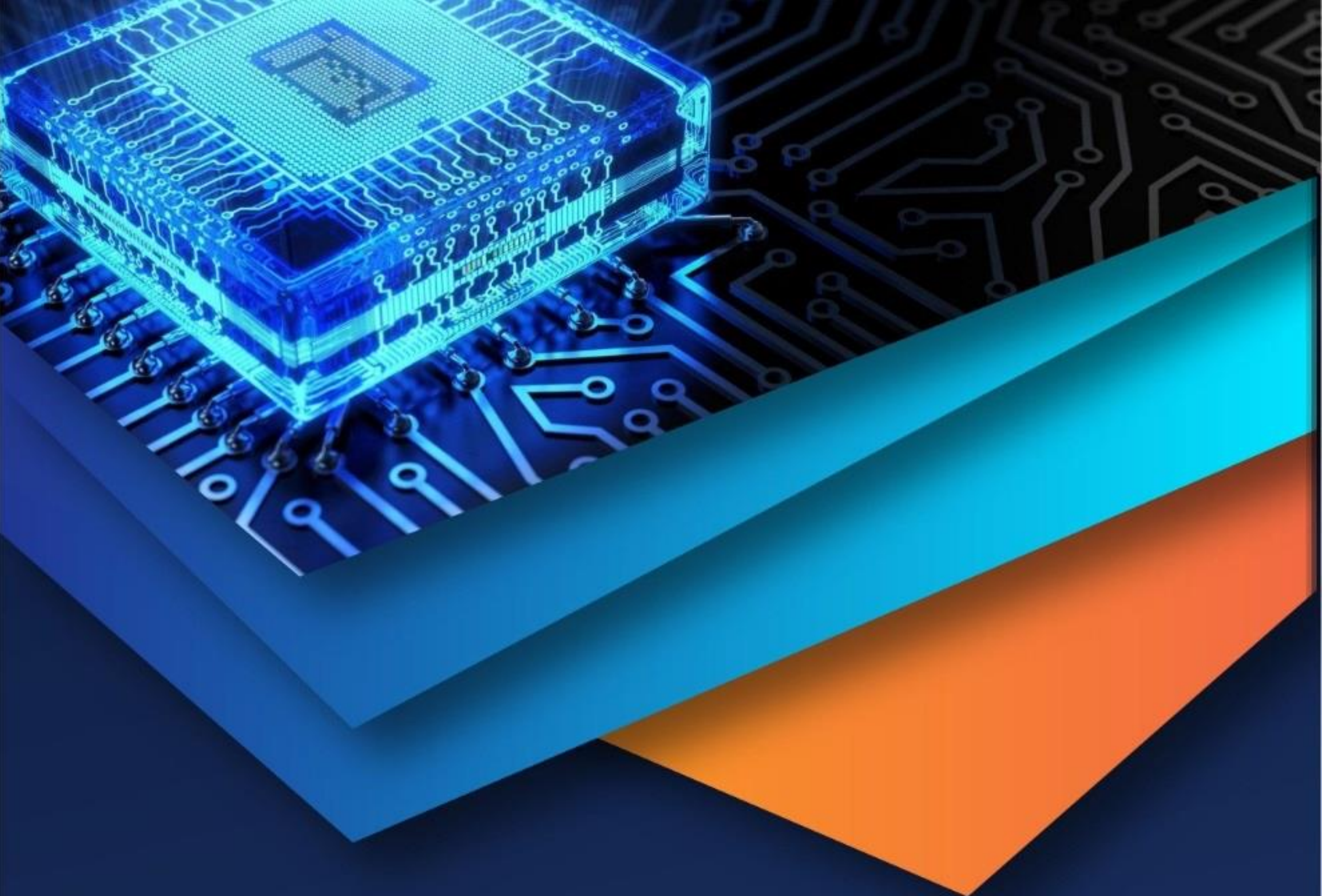

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