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Design, Fabrication and Characterization of a Piezoelectric Ultrasonic Transducer

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Abstract

This work has been done to realize a piezoelectric ultrasonic transducer, almost from scrap materials. The shape and size of the device were determined by considering practical limitations and for the ease of fabrication. The device was realized by conventional manufacturing processes. An aluminum plate was clamped in between two massive acrylic plates. These two massive plates having central holes were clamped together with nuts and bolts. This makes the aluminum plate as a diaphragm with fixed boundary condition at the circumference of the central hole. Two Lead (Pb)-Zirconium (Zr)-Titanate(Ti) (PZT) patches were glued unto the aluminium plate on its two faces concentric with the central holes of the two massive plates. The transducer can act both as an actuator and a sensor. Two PZT patches are meant for actuation and sensing of the vibration of the aluminum plate. The finite element analyses were performed using the commercial package ANSYS and plotted in MATLAB. The frequency response of the device was obtained from harmonic analysis in ANSYS. The actual natural frequency was determined experimentally using Laser Doppler Vibro-meter (LDV) and compared.

Keywords: *Design, Fabrication; Characterization; Piezoelectric; Ultrasonic Transducer.*

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INTRODUCTION

Now-a-days, the ultrasonic sensing techniques have got wide range of applications e.g., non-destructive testing, medical imaging, proximity sensing, etc.

Ultrasonic transducers are those transducers that operate in the ultrasonic range. The frequency range of acoustic waves exceeding the human audible range (20 Hz - 20 kHz) is called ultrasonic range.

Transducer is a device which converts one form of energy into other. In electromechanical system, the electrical energy is converted into mechanical energy and vice versa. They are of two types one is actuator, and another is sensor. When the electrical energy is converted into mechanical one to excite any structure, is called actuation. And when the mechanical vibration energy is converted into and represented in terms of electrical energy, is called sensing.

Piezoelectricity is the property of certain materials called piezoelectric materials. By virtue of which if the material is subjected to mechanical stress it generates charge distribution and thus there is voltage difference between two electrodes. This is known as direct piezoelectric effect. The reverse piezoelectric effect causes mechanical strain on the material by the application of electrical voltage. When an AC voltage is applied, it starts vibrating and thus generates mechanical or pressure waves at the same frequency of applied AC voltage. This reverse piezoelectric effect is usually used as actuator which converts electrical energy into mechanical energy. Similarly, the direct piezoelectric effect can be used in sensing the mechanical displacements by measuring electrical voltage produced due to the resulting mechanical stress. Both actuators and sensors are the transducers which convert one form of energy into another [1].

The piezoelectric effect was first mentioned in 1817 by the French mineralogist Rene Just Hauy [2]. It was first demonstrated by Pierre and Jacques Curie in 1880 [3]. Their experiments led them to elaborate the early theory of piezoelectricity. This theory of piezoelectricity was complemented by the further work of G.Lippman, W.G.Hankel, Lord Kelvin and W. Voigt in early 20th century [4].

Application of the piezoelectric effect in practice started in 1917 when Paul Langevin suggested using an ultrasonic echo ranging device for detection of underwater objects [5]. The first piezoelectric microphones, phones, sound

pickups, devices for sound recordings, devices for vibration measurements, forces and accelerations, etc. were created soon after Langevin’s invention. The first piezoelectric plate application for measuring the acoustic properties of a substance was introduced by G. Pierse in 1925[6]. The most important application of piezoelectricity for practical purposes, the first ultrasonic flaw detector (non- destructive testing) was invented by C. Sokolov [7]. The first working piezoelectric transducer based on barium titanate (BaTiO3) came to existence by R.
B. Gray (1945). PZT solid solution was first developed by G Shirane and K Suzuki (1952). PZT the best suitable piezoelectric material was established by the extensive study of H Jaffe, K Jaffe, W R Cook, Jr., D Berlincourt, R R Gerson (1955-71). They were the heart of the development of PZT ceramics.

The scope of piezoelectric transducers extensively grown to variety of new areas, such as ultrasonic medical therapy and diagnostics, level gauges, devices for continuous industrial control and other devices with wide range of applications were found for piezoelectric transducers. The knock sensors, the distance sensors, the fuel injection systems, vibration control systems based on piezoelectric ultrasonic transducers have vast application in automobile industry [8]. This principle also greatly entered into MEMS in the name of piezoelectric micro-machined ultrasonic transducers PMUT [9-10].

This paper includes not only design, and development, but also experimentation validating numerical results.

MATHEMATICAL MODEL

Piezoelectricity is the coupling between electrical voltage and mechanical stress. It is the property of the material by which electricity is produced by the application of pressure and vice versa [1].

Piezoelectric Relations

The electrical behavior at constant stress or of an unstressed medium under the influence of an electric field is defined by two quantities, the field strength (E), and the dielectric displacement (D). Their relationship is given by

$$D = \varepsilon^{\sigma} E \quad (1)$$

Here ‘ε^{σ}' is the permittivity at constant stress or of the (unstressed) medium.

The mechanical behavior of the same medium at zero electric field strength is defined by two mechanical quantities, the stress applied (σ), and the strain (ϵ). Their relationship is given by

Here 'S^{E}' denotes the compliance of the medium (at zero electric field).

Piezoelectricity involves the interaction between the electrical and mechanical behavior of the medium. To a good approximation this interaction can be described by linear relations between electrical and mechanical variables (σ and E)

$$\epsilon = S^{E}\sigma + d'E \qquad (2)$$

$$\epsilon = S^{E}\sigma \qquad (3)$$

$$D = d\sigma + \varepsilon^{\sigma}E$$

These two equations are known as the strain form of piezoelectric equations.

The second set of piezoelectric equations, known as stress form, can be obtained from the first set as follows

$$\epsilon = {C^{E}}^{-1}\sigma + d'E \qquad (5)$$

$$\sigma = C^{E}\epsilon - C^{E}d'E \qquad (6)$$

$$\sigma = C^{E}\epsilon - eE \qquad (7)$$

Where, $C^{E}d'$ is piezoelectric stress matrix, C^{E} is the stiffness matrix which is the inverse matrix of compliance matrix S^{E}. Thus

$$e' = (C^{E}d')' \qquad (8)$$

$$e' = (d')'(C^{E})' \qquad (9)$$

$$e' = d(C^{E})' \qquad (10)$$

$$e' = dC^{E} \qquad (11)$$

As 'C^{E}' is a symmetric tensor.

Substituting Eq. (7) in Eq. (4), we have

$$D = d(C^{E}\epsilon - eE) + \varepsilon^{\sigma}E \qquad (12)$$

$$D = dC^{E}\epsilon + (\varepsilon^{\sigma} - de)E \qquad (13)$$

$$D = e'\epsilon + \varepsilon^{\epsilon}E \qquad (14)$$

de) is permittivity at constant strain (clamped permittivity).

Thus the stress form of piezoelectric equations are given by

$$\sigma = C^{E}\epsilon - eE \qquad (15)$$

$$D = e'\epsilon + \varepsilon^{\epsilon}E \qquad (16)$$

Piezoelectric Matrices

Stiffness and compliance matrix

Piezoelectric materials are transversely isotropic. Transversely isotropic materials are a special class of orthotropic materials having the same properties in one plane

(E.g. the x-y plane) and different properties in its normal direction (e.g. the z-axis). Such materials are described by 5 independent elastic constants, instead of 9 for fully orthotropic materials.

The only 5 independent elastic constants are: s^E_{11}, s^E_{33} s^E_{44} s^E_{12} ands^E_{13} And we have $s^E_{22} = s^E_{11}$ $s^E_{55} = s^E_{44}$ $s^E_{66} = 2(s^E - s^E_{12})$, $s^E_{23} = s^E$ and other coefficients are zero. So we have 'S' matrix is given as

$$[S^E] = [C^E]^{-1} = \begin{bmatrix} s^E_{11} & s^E_{12} & s^E_{13} & 0 & 0 & 0 \\ s^E_{12} & s^E_{11} & s^E_{13} & 0 & 0 & 0 \\ s^E_{13} & s^E_{13} & s^E_{33} & 0 & 0 & 0 \\ 0 & 0 & 0 & s^E_{44} & 0 & 0 \\ 0 & 0 & 0 & 0 & s^E_{44} & 0 \\ 0 & 0 & 0 & 0 & 0 & 2(s^E_{11} - s^E_{12}) \end{bmatrix}$$

There are three ways in which a user can input stress-strain data. A user can input an anisotropic elastic matrix with TB, ANEL. The TBOPT field of the TB command controls whether this is read as a stiffness or compliance matrix (TBOPT=1 for compliance input and TBOPT=0 for stiffness input). Otherwise, one can use MP commands to specify orthotropic material properties (EX, NUXY, GXY). Where,

$$E_x = E_y = \frac{1}{s^E_{11}}, E_z = \frac{1}{s^E_{33}},$$

$$G_{xy} = G_{yz} = \frac{1}{s^E_{44}}, G_{zx} = \frac{1}{2(s^E_{11} - s^E_{12})},$$

$$\upsilon_{xy} = -\frac{s^E_{12}}{s^E_{11}}, and\ \upsilon_{yz} = \upsilon_{zx} = -\frac{s^E_{13}}{s^E_{33}} \tag{19}$$

$$[S^E] = [C^E]^{-1} = [D]^{-1} = \begin{bmatrix} \frac{1}{E_x} & \frac{-\upsilon_{xy}}{E_y} & \frac{-\upsilon_{zx}}{E_z} & 0 & 0 & 0 \\ \frac{-\upsilon_{xy}}{E_y} & \frac{1}{E_y} & \frac{-\upsilon_{yz}}{E_z} & 0 & 0 & 0 \\ \frac{-\upsilon_{zx}}{E_z} & \frac{-\upsilon_{yz}}{E_z} & \frac{1}{E_z} & 0 & 0 & 0 \\ 0 & 0 & 0 & \frac{1}{G_{xy}} & 0 & 0 \\ 0 & 0 & 0 & 0 & \frac{1}{G_{yz}} & 0 \\ 0 & 0 & 0 & 0 & 0 & \frac{1}{G_{zx}} \end{bmatrix}$$

Piezoelectric matrix

As per Eq. (3) and Eq. (4), the piezoelectric matrix ($\boldsymbol{d_{3X6}}$) is the coupling between mechanical stress ($\boldsymbol{\sigma_{6X1}}$) and electric field strength ($\boldsymbol{E_{3X1}}$). The only 3 independent piezoelectric coefficients are: $\boldsymbol{d_{33}}$, $\boldsymbol{d_{31}}$ and $\boldsymbol{d_{15}}$. And we have $\boldsymbol{d_{32}} = \boldsymbol{d_{31}}$ and $\boldsymbol{d_{24}} = \boldsymbol{d_{15}}$, and other coefficients are zero. So we have 'd' matrix

$$[d] = \begin{bmatrix} 0 & 0 & 0 & 0 & d_{15} & 0 \\ 0 & 0 & 0 & d_{15} & 0 & 0 \\ d_{31} & d_{31} & d_{33} & 0 & 0 & 0 \end{bmatrix} \tag{20}$$

Permittivity matrix

$$[\varepsilon^\sigma] = \begin{bmatrix} \varepsilon^\sigma_{11} & 0 & 0 \\ 0 & \varepsilon^\sigma_{11} & 0 \\ 0 & 0 & \varepsilon^\sigma_{33} \end{bmatrix} = \varepsilon_0 \begin{bmatrix} K^\sigma_{11} & 0 & 0 \\ 0 & K^\sigma_{11} & 0 \\ 0 & 0 & K^\sigma_{33} \end{bmatrix} \tag{21}$$

where, $\boldsymbol{K^\sigma_{11}} = \varepsilon^\sigma_{11} / \varepsilon_0$ is relative permittivity.

In ANSYS, although the user has the

choice of inputting permittivity as an absolute value or relative value, the relative value is the recommended choice.

DESIGN AND FABRICATION

Design of the Piezoelectric Ultrasonic transducer

The first and foremost requirement is to have a ultrasonic device. This means that the resonant frequency of the device should be in the ultrasonic range which i more than 20 kHz. The shape of the device was chosen to be circular for the ease of manufacturing, by drilling hole. The size was determined by considering two aspects; one the size of the drill bit available in the workshop, and the size of the PZT patches available in the lab. The thickness of the aluminum diaphragm was selected to be 1 mm considering the following factors

- higher the thickness, higher will be the frequency and
- Higher the thickness, lower will be the deflection.

The modal analysis was carried out in ANSYS and the Figure 1 shows the variation of resonant frequency with diameter of the aluminum diaphragm plotted in MATLAB.

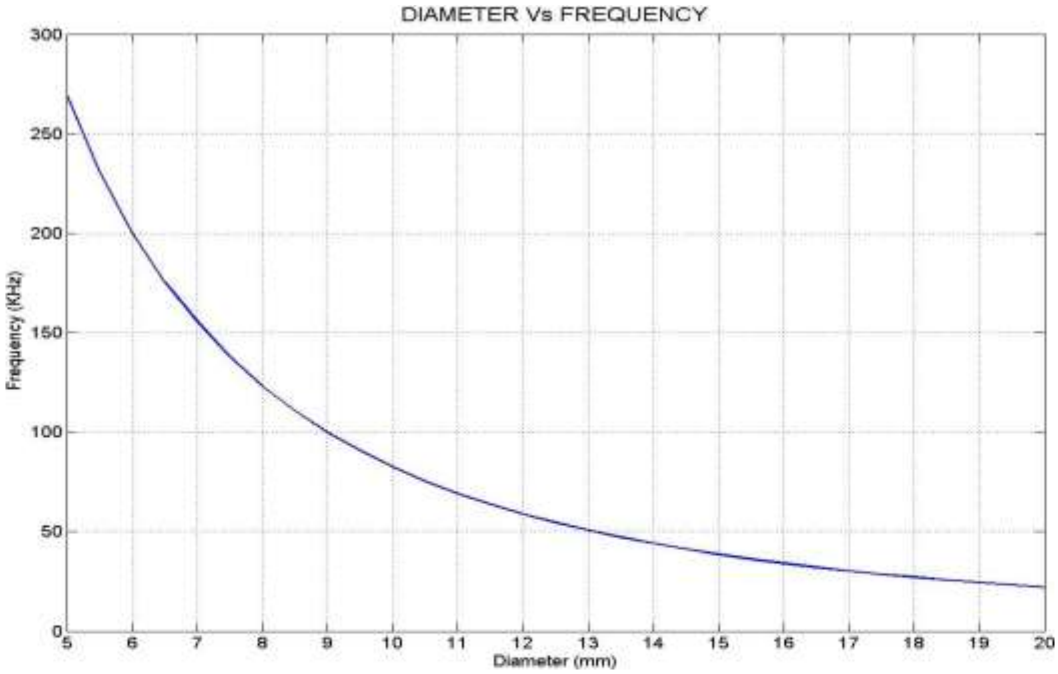

Figure 1: Diameter Vs Frequency curve obtained from Modal Analysis using ANSYS

The PZT patches available in the lab were of diameter 10 mm and 8 mm. Also the maximum diameter of drill bit available in the workshop was 12 mm. Therefore the diaphragm diameter was selected to be 12 mm. And the corresponding frequency from the Figure 1 was found to be 58.8 kHz which is in ultrasonic range.

The fixed boundary condition of the aluminum diaphragm can be obtained by clamping the 1mm aluminum plate without hole in between two other acrylic massive plates having coinciding holes at the center.

Fabrication of the Piezoelectric Ultrasonic Transducer

The device was fabricated using pieces of scrap material. We collected some scrap acrylic from the workshop. 50X50 mm2 plates were cut out of the discarded blocks. Two plates, top and bottom, were required for one device.

All the three plates, namely top and bottom acrylic plates, and an aluminum plate in between, were held together and outer holes were drilled for clamping. Then the middle plate, i.e., the aluminum plate was removed and two acrylic plates were clamped using nuts and bolts. A 12 mm hole was drilled at the center of two plates clamped together. Now the aluminum plate was inserted in between the two plates and bolts were tightened again. This arrangement resulted in an aluminum diaphragm in the center with fixed boundary condition on the edges.

The next step was to put PZT patch on the diaphragm. The PZT patches available in the lab have two electrodes on both top and bottom faces. If the PZT patch was glued to the diaphragm using a general purpose adhesive, one of the electrodes would have been lost. Therefore we had to use a conductive adhesive. The ‘silver paste’ which is a conductive adhesive was used for the purpose of gluing PZT patch on the diaphragm.

The use of silver paste has its own limitations – it needs to be cured for 20 minutes at 120 oC, and even after that the patch was not sticking properly. After trying for several times, a device was successfully fabricated as shown in Figure

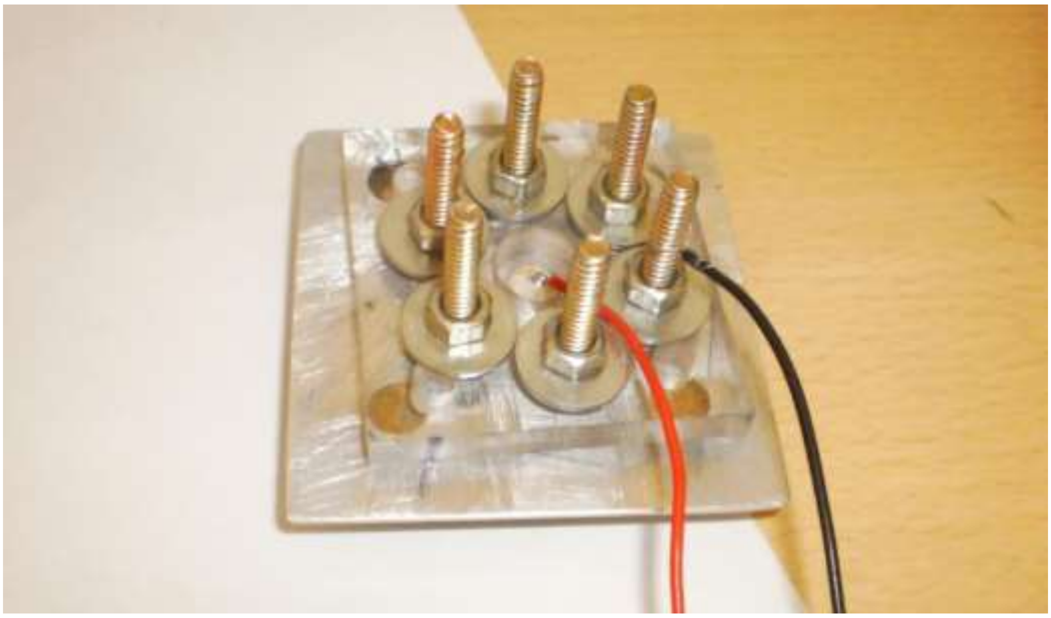

Figure 2: Piezoelectric Ultrasonic Transducer

Table 1: Dimensions of the device

Material	Diameter (mm)	Thickness (mm)
Aluminium	12	1
PZT Patch	10	1

Table 2: Properties of Aluminum

Material	Elasticity (E) in GPa	Poisson's Ratio (ν)	Density (ρ) in kg/m^3
Aluminium	55	0.34	2700

CHARACTERIZATION OF THE ULTRASONIC TRANSDUCER

Numerical Analysis

Harmonic analysis was performed using finite element calculation in ANSYS. For harmonic analysis, the physical dimensions of the device are given in the Table 1, the properties of the aluminum are given in the Table 2 and the properties of PZT patches are given in the Table 3 respectively.

Table 3: Properties of PZT patches

Piezoelectric Constants (C/N)		Die electric Constants		Elastic Constants (m^2/N)		Physical Constants	
d_{33}	$400X10^{-12}$	$\varepsilon^{\sigma}_{33}/\varepsilon_0$	1750	s^E_{11}	$19X10^{-10}$	ρ	7700 (kg / $m^{3)}$
d_{31}	$-170X10^{-12}$	$\varepsilon^{\sigma}_{11}/\varepsilon_0$	1290	s^E_{33}	$16X10^{-10}$	T_c	360^0 C
d_{15}	$500X10^{-12}$	-	-	s^E_{44}	$31.9X10^{-10}$	-	-
-	-	-	-	s^E_{12}	$-307X10^{-10}$	-	-
-	-	-	-	s^E_{13}	$-408X10^{-10}$	-	-

Experimental Modal Analysis

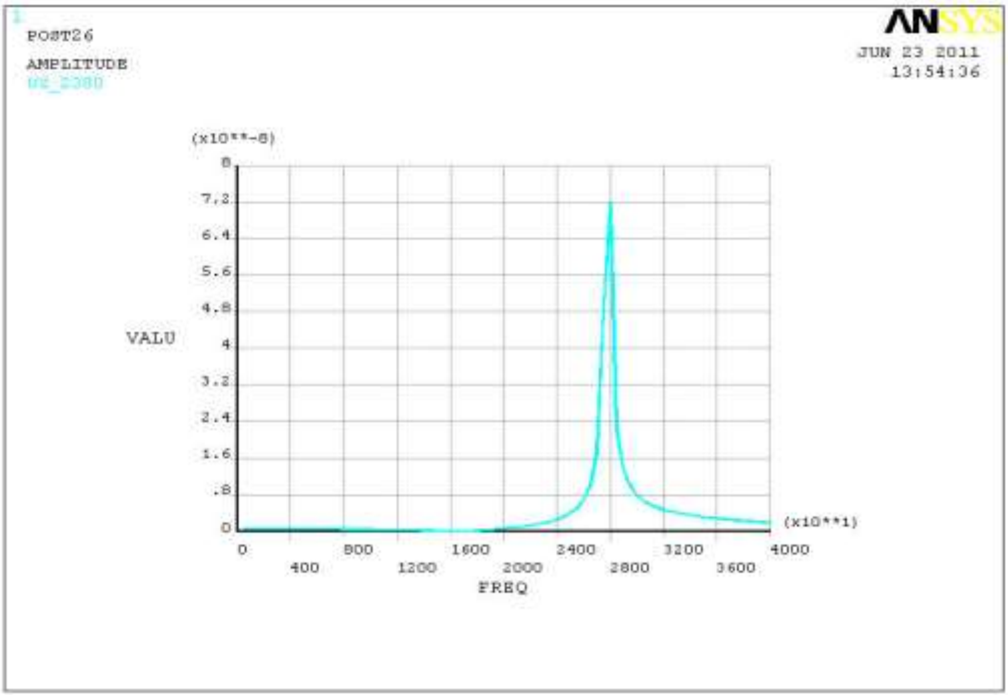

Figure 3: Frequency Response Function (FRF) of the Device obtained from ANSYS

Figure 3 shows the frequency response function of the device obtained from harmonic analysis in ANSYS. The resonant frequency of the device was found to be 28 kHz as shown in the Figure 3.

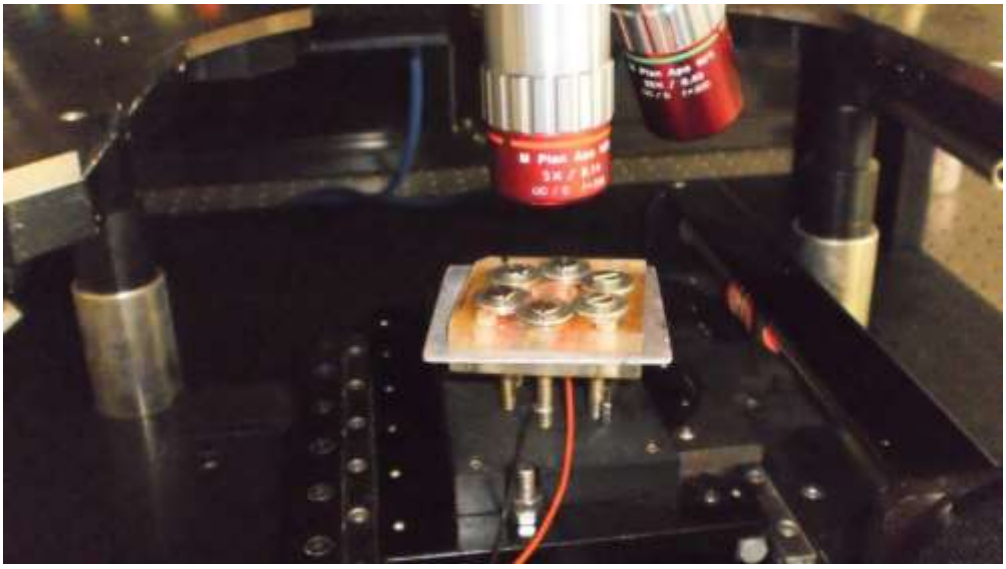

Figure 4: Experimental Setup; Device under Test (DUT) using Laser Doppler Vibro-meter (LDV)

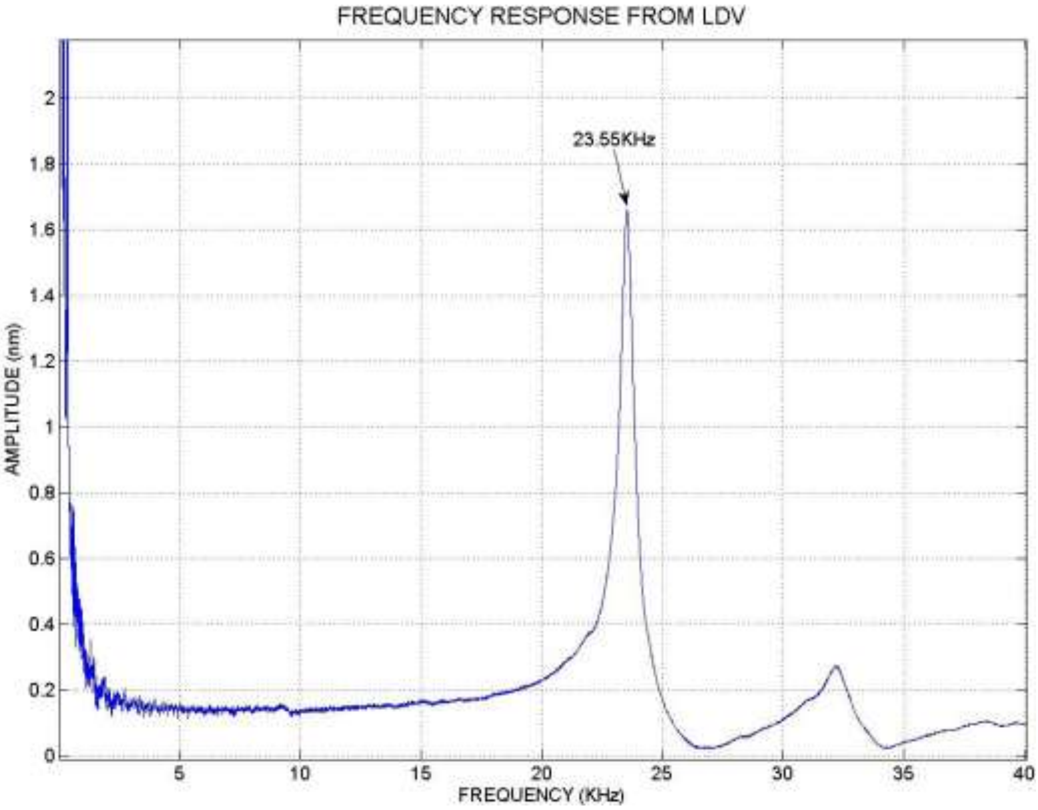

Figure 5: Actual frequency response of the device obtained from LDV

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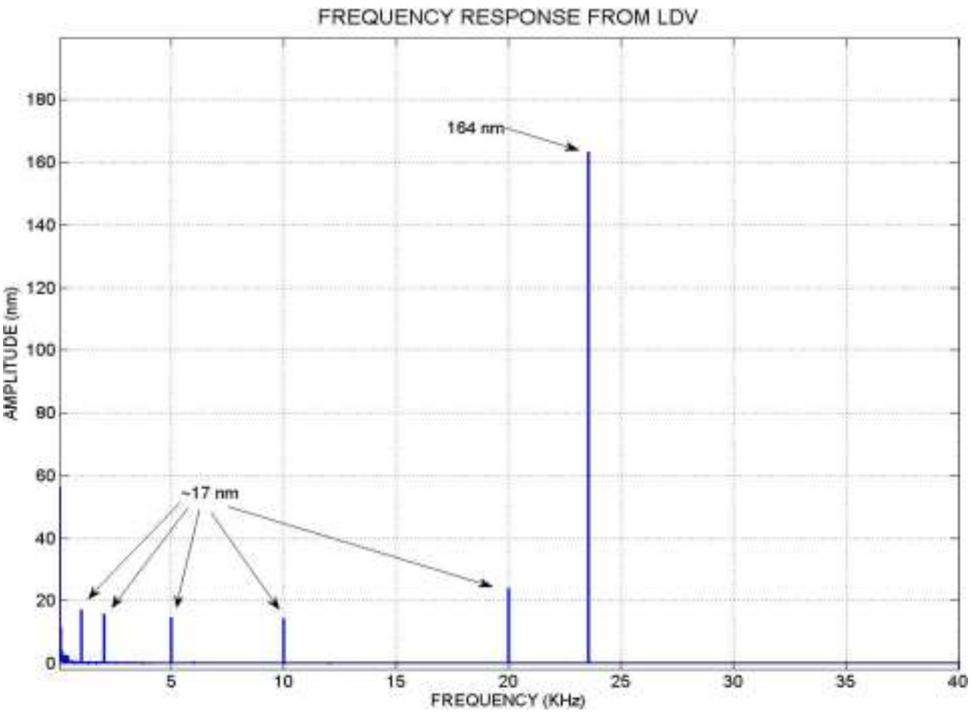

Figure 6: Response of the Device at Different Frequencies Obtained from LDV

The actual natural frequency was determined by performing experimental modal analysis using Laser Doppler Vibro-meter (LDV). The setup is shown in the Figure 4. The actual Frequency response is shown in Figure 5. The resonant frequency of the device was found to be 23.55 kHz from the experimental data.

The response at different frequencies was found out by applying sinusoidal voltage (same amplitude of 10 V) with varying the frequency. It was observed that at resonant frequency the amplitude of vibration increased by almost one order. At other frequencies (1, 2, 5, 10, and 20 kHz), the amplitude was ≈17 nm. But the amplitude of vibration corresponding to resonant frequency (23.55 kHz) was ≈164 nm which is about 10 times higher. This is shown in Figure 6.

CONCLUSION

The piezoelectric transducer was designed and fabricated from scrap materials. Numerically the resonant frequency were calculated in ANSYS and found to be 28 kHz. Experimental characterization of the device was carried out using Laser doppler vibrometer and the resonant frequency was found to be 23.55 kHz. The piezoelectric ultrasonic transducer developed, can be used as vibration energy harvester by converting the vibration energy being wasted into electrical energy and utilizing as power source for small power consumption systems.

The deviation of the numerical result from the experimental result may be attribute to the reasons like, the clamped boundary condition may not be achieved by tightening nuts and bolts, the actual properties of the materials in device fabricated may not be the same as that of the values taken for numerical analysis in ANSYS.

REFERENCES

1. Prasanta Kumar Samal, 2011, "Fabrication and Characterization Of Piezoelectric Micromachined Ultrasonic Transducer (PMUT) For Liquid Level Sensing." ME Thesis, Department of Mechanical Engineering, Indian Institute of Science, Bangalore.

2. First observation of the presence of electric charges on the surface of a stressed tourmaline crystal.

3. Mathematical deduction of the inverse piezoelectric effect, confirmed experimentally by P. & J. Curie: 1881. W.G.Hankel introduced the term piezoelectricity.

4. P. Langevin, 1918, Ultrasonic echo ranging device for detection of underwater objects.

5. G.W. Pierce, 1925, Piezoelectric oscillators applied to the precision measurement of the velocity of sound in air and CO2 at high frequencies. Proc. Amer. Acad. 60, 271–3021925.

6. S.Ya. Sokolov, 1928, Way and the device for test of metals. The copyright certificate USSR.

7. Jürgen Nuffer, Thilo Bein , 2006, Application of piezoelectric materials in transportation industry, Global Symposium on Innovative Solutions for the Advancement of the Transport Industry, 4.-6. October 2006, SanSebastian, Spain

8. Aman P V, 2010 ,"Design, Optimization and Fabrication of a PZT based Micro-machined Ultrasonic Transducer (PMUT)" Department of Mechanical Engineering, Indian Institute of Science, Bangalore.