In-Bore Pressure Measurement:
Application of MEMS Piezoelectric Sensor for Mortar Launch Vehicle

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Abstract: *MEMS(Microelectromechanical system) is a technology that is ruling the industry by the production of different sensors and actuators. Pressure sensors are one of the most widely used micro-devices, around 25 million pressure sensors are manufactured every year for different applications. In the proposed context, a Piezoelectric pressure sensor using PZT (Lead Zirconate Titanate) is designed, and the Stress, Displacement, Electric potential and Frequency parameters of the sensor are analyzed using a software tool called COMSOL Multiphysics. The sensor frequency is then matched with the application where the in-bore pressure of a mortar is measured and found to be 3.6Mhz.*

Keywords: MEMS, COMSOL Multiphysics, Piezoelectric pressure sensor**.**

1. Introduction

The Micro-electromechanical systems (MEMS) have attracted many researchers since past two decades especially into micro sensors and actuators. Pressure sensors are one among them. Major benefits of using MEMS pressure sensors are small size, low cost and high performance. These pressure sensors have been based on various physical properties like piezoresistive, piezoelectric, capacitive, magnetic and electro-static. But as compared to other MEMS technologies, piezoelectric MEMS recommend great rewards. In the family of crystals, certain materials are called as piezoelectric because of their property to generate voltage when suitable pressure is applied on them, vice versa is also possible that is when the voltage is applied, the crystal starts vibrating. COMSOL Multiphysics – software environment providing all modelling stages (definition of geometrical parameters, description of physics, visualization etc.) for the simulation of any physical processes that can be represented as a system of differential equations in partial derivatives. It can be: structural mechanics, heat transfer, engineering chemistry (including the chemical kinetics), electrical engineering, acoustics, geophysics and the microlevel related phenomena, optical and high frequency effects. There is also set of additional modules for various applied tasks for this package.

2. Model Description

A square Diaphragm of side length 95μm and thickness 2μm is constructed as shown in the Fig. 1. Another patch of side length 5μm is constructed to mark the maximum displacement region. The diaphragm material is polysilicon. To place the piezoelectric patches, the maximum stress region in the diaphragm must be located. For this a load of 1[Pa] is applied on the top face of the silicon diaphragm.

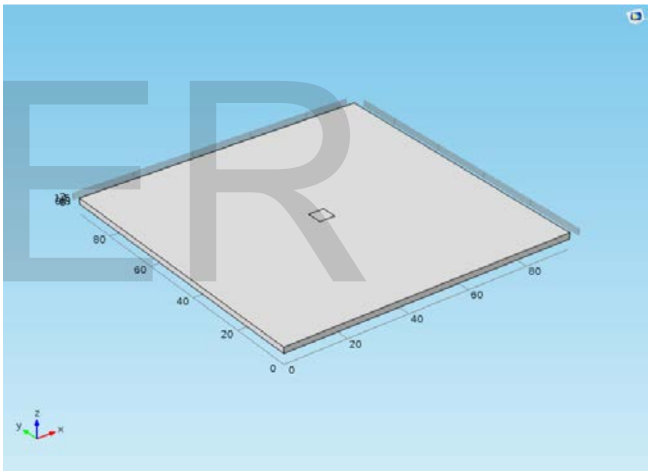

Fig. 1. Model Geometry(μm)

The result of application of load at the center results in maximum stressed regions. This can be graphically represented in the Fig. 2.

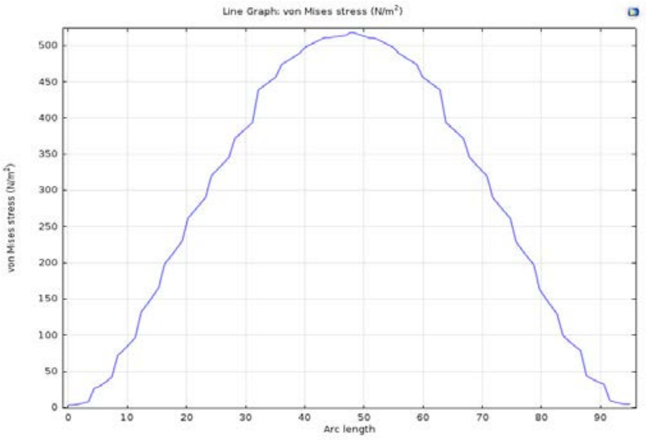

Fig 2. Stress versus Arc length graph

TABLE I.

Material	Side Length (μm)	Thickness (μm)
Silicon Diaphragm	95×95	2
Piezoelectric Patch	47.5×9.5	1
Minor Patch	5×5	1

The dimension of various materials of the sensor is shown in Table I. With reference to Fig. 2, the piezoelectric patches are placed at the edges of the silicon diaphragm where maximum stress is seen. This is shown in the Fig. 3.

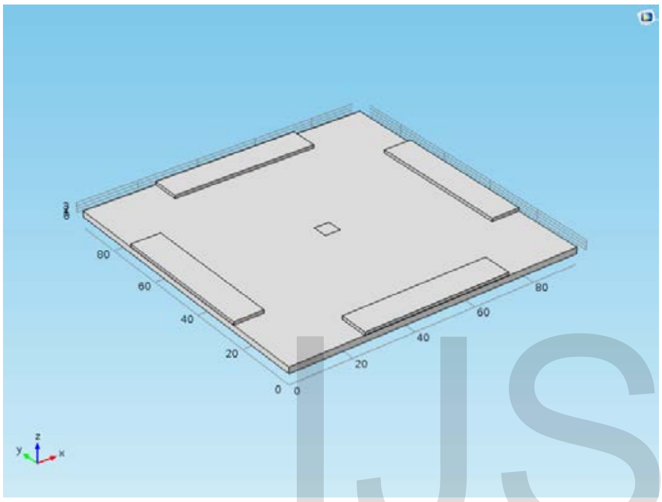

Fig. 3. Patch arrangement(μm)

The software uses FEM(Finite element method) to compute the model in Fig. 3. This is called as Meshing. The FEM is a stiffness-based method in which the entire problem domain is divided into subdomains called elements. The set of elements make up a domain as shown in the Fig. 4. Each element is described by a set of nodes whose connectivity completely describes the element in FE space.

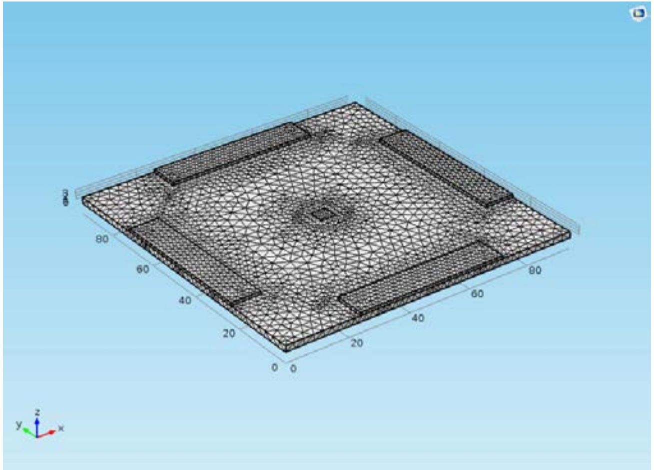

Fig. 4. FEM Analysis.

3. Mathematical modelling

Various Properties of sensors such as stress, displacement, electric potential and Resonant frequency are calculated using the mathematical equations. The Maximum stress in a silicon diaphragm for a unit pressure is given by the equation (1).

$$\sigma = 0.378\, p\, \frac{a^2}{h^2} \qquad (1)$$

Where,
σ = stress (N/m^2)
p = Applied pressure in Pascal (1 Pa)
a = side length of the silicon membrane
h = thickness of the silicon membrane

From equation (1) it is evident that on the application of pressure there is stress in the diaphragm, as the pressure is applied on the diaphragm there is notable displacement, this expressed in the equation (2). The equation (3) gives the Flexure rigidity, which is a measurement of stiffness of the diaphragm.

$$w = 1.33 * 10^{-3}\, p\, \frac{a^2}{16R} \qquad (2)$$

and $R = \frac{Eh^3}{12(1-\gamma^2)}$ (3)

Where,
w = Displacement
p = Applied pressure in Pascal (1 Pa)
a = Side length of the silicon membrane
h = Thickness of the silicon membrane
R = Flexure rigidity of the silicon diaphragm
E = Young’s module
γ = Poisson’s ratio

The PZT-5H is placed on maximum stress regions of a silicon diaphragm which leads to the generation of electric potential at the output. Hence, charge density is a measure of electric charge per unit volume of space, one, two or three dimensions.
Charge density is given by equation (4)

$$D = d_{33} * \sigma \qquad (4)$$

Where,
D = Charge density
σ = Mechanical stress
d_{33}= Piezoelectric strain co- efficient

On the application of pressure, the PZT-5H produces electric potential that can be calculated using equation (5). Equation (6) gives the capacitance. When the patch is placed on the diaphragm, a dielectric is formed in the interfacing of the silicon diaphragm and the PZT-5H.

$$V = \frac{Q}{C} = \frac{D*A}{C} \qquad (5)$$

$$C = \frac{\varepsilon_0 \varepsilon_r A}{d} \qquad (6)$$

Where,
V= Electric Potential (voltage)
Q= Charge accumulated.

ε_0=Permittivity of free space (8.854$*10^{-12}$).
ε_r= Relative permittivity of PZT – 5H.
A= Area of PZT – 5H.
d= Thickness of PZT – 5H (1µ).
C= Capacitance

The Resonant frequency is defined as the frequency of the diaphragm without any input constraints. This is expressed using equation (7)

$$f = \frac{0.47\,t}{a^2}\sqrt{\frac{E}{\rho(1-\gamma^2)}} \qquad (7)$$

Where,
f= Resonant frequency.
t= Thickness of the silicon diaphragm.
ρ= Density of silicon membrane.
a= Side length of the silicon diaphragm.
E= Young's modulus of silicon diaphragm.
□= Poisson's ratio.

The Parameters used in the computation of theoretical values are listed below in Table II.

TABLE II.

	Young's Modulus (GPa)	Poisson's Ratio	Density (Kg/m^3)	Permittivity
Silicon	150	0.17	2329	2859
PZT-5H	60	0.34	7500	25.32E9

4. Simulation and results

The stress analysis is shown in the Fig. 6. The maximum stress is at the edges. This can be seen by the color legend bar displayed at the right side of the sensor. Red constitutes maximum stress and blue, minimum stress.

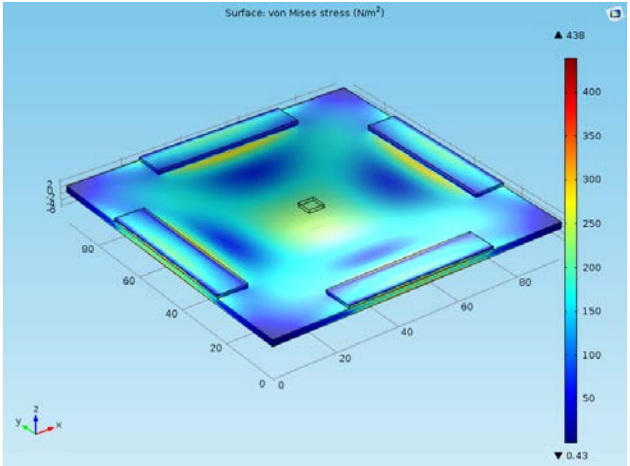

Fig. 6. Stress plot of PZT-5H.

In the displacement graph in Fig. 7, the maximum deformation is observed at the center of the diaphragm. This due to the load applied on the diaphragm. Due to the deformation at the center, maximum stress region is formed at the edges.

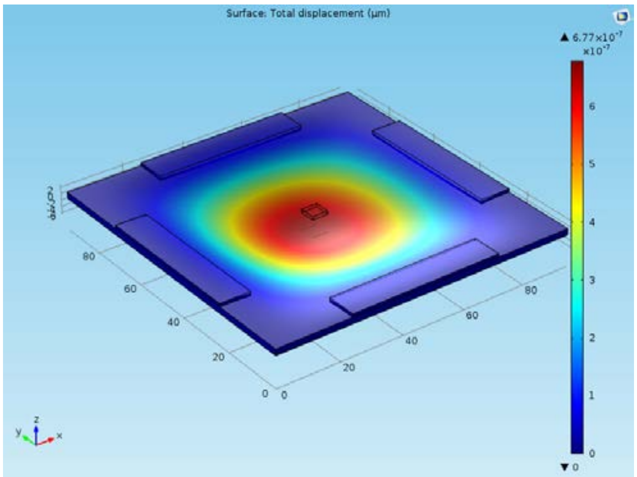

Fig. 7. Displacement plot of PZT-5H

Since the PZT-5H patches are placed at the maximum stress regions, Piezoelectric effect is seen. That is, due to the stress experienced, the PZT will produce Electric potential as the output. This can be seen in the Fig. 8.

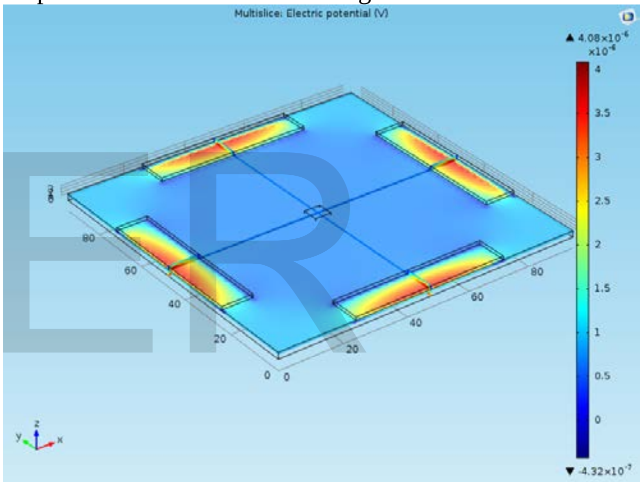

Fig. 8. Electric potential plot of PZT-5H

The comparison of theoretical and practical values of Stress, Displacement and Electric potential is listed in the Table III.

TABLE III.

Study	Theoretical	Simulation
Stress(N/m^2)	853	438
Displacement(µm)	5.028E-6	6.77E-7
Electric Potential (V)	4.08E-6	2.189E-5
Eigen Frequency (MHz)	1.02	3.6

A. Pressure versus Electric potential.

The variation of Electric potential with respect to pressure is shown in the Fig. 9. From the plot, it is seen that the Electric potential varies Linearly with respect to the pressure applied. The PZT material is said to be more sensitive, because it produces more Electric potential with minimal pressure applied.

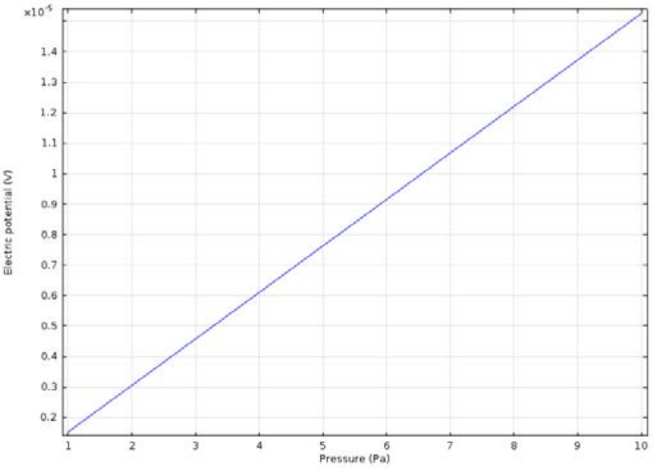

Fig. 9. Pressure versus Electric Potential

B. Frequency Domain.

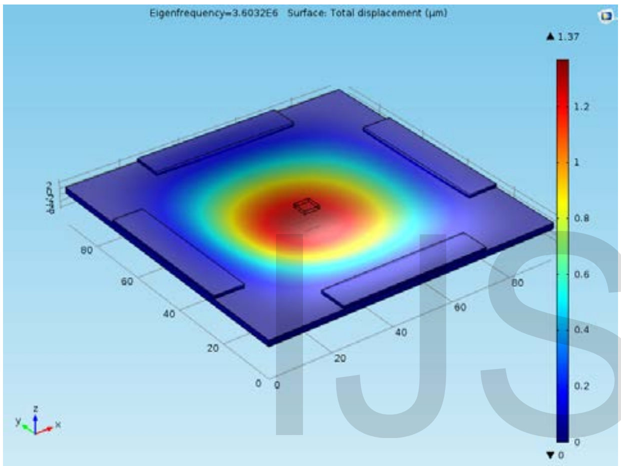

Fig. 10. Eigen Frequency plot of PZT-5H.

The 3D Eigen frequency plot of the sensor is shown in Fig. 10. Eigen frequency is defined as the natural frequency long with the frequency induced due to the application of pressure. From Table III, the theoretical and practical frequencies are observed. The 1D plot is shown in the Fig. 11. The peak represents the optimal frequency value of the sensor.

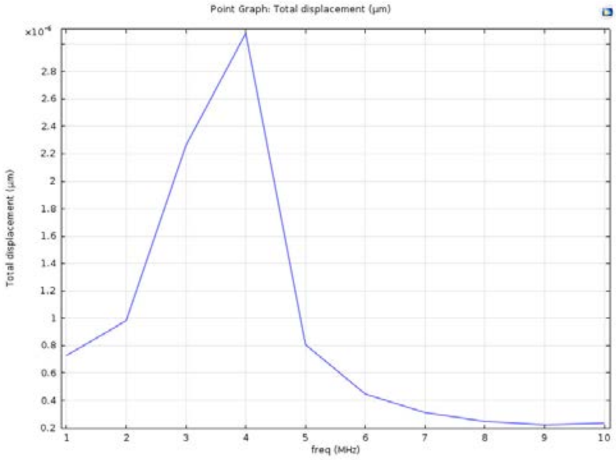

Fig. 11. Displacement versus Frequency plot

5. Conclusion

MEMS pressure sensor is modelled and analyzed using COMSOL tool. Dimension and pressure constraints are applied to Lead Zirconate Titanate (PZT-5H) and the properties such as Stress, Displacement Electric potential and Frequency are obtained. The PZT (Lead Zirconate Titanate) is used because of high sensitivity to the applied pressure. Thus, due to the rigidity of Piezoelectric pressure sensors, these can be used in harsh environments and can sense dynamic pressure variations.

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