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Dynamic and Stationary Performance Analysis of Diaphragm Based Acoustic Pressure Sensor

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***Abstract**: Pressure sensing and measurement are of utmost importance in many of the process industries and biomedical applications. The key element of the pressure sensor is diaphragm and the diaphragm design including shape and dimensions play a major role in sensitivity of pressure sensor irrespective of the type of sensor viz. capacitive, piezoresistive or piezoelectric sensor. The acoustic pressure sensors require the proper analysis of dynamic performance of the key element since the acoustic source is dynamic pressure. This paper presents the stationary and dynamic performance analysis of diaphragm for piezoelectric acoustic pressure sensor. The analysis has been done for better deflection of the diaphragm and optimized stress and strain in order to achieve maximum sensitivity. In design step, at first the diaphragm is analysed for natural frequency, modal frequencies and bandwidth of the structure since the piezoelectric resonant sensors can be used for sensing whenresonant frequency of the membrane is at least 3 to 5 times the highest applied frequency and for energy harvesting applications, when it is almost equal to the applied frequency.Hence, a comparison of shapes of diaphragm, with their fundamental and modal frequencies, deflection, and stress and strain is established. Further a resonant sensor structure is also analyzed for dynamic performance with cavity neck of different size to understand the importance of cavity neck in dynamic performance of the sensor. The circular diaphragm is found be the best choice from the point of view of maximum deflection and natural frequency and the structure with cavity neck has better bandwidth and deflection.*

***Keywords**: Acoustic Sensor, Diaphragm Based, Natural Frequency, Piezoelectric.*

I. INTRODUCTION

Piezoelectric acoustic pressure sensors often find applications in automotive, aerospace and biomedical engineering. These sensors can be miniaturized, no external power supply needed, very sensitive with good performance and can be mass produced. The diaphragm is the key element and the diaphragm design can be done by Finite Element Modeling (FEM) to analyze the deflection, stress and strain distribution, natural frequency and the dynamic performance parameters.

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The design and fabrication of the diaphragm-based pressure sensor is of focused research to increase the sensitivity, voltage generated and optimizing the natural frequency in acoustic range and increasing the bandwidth by different manufacturing technologies like bulk and surface micromachining.[1]-[5]. These sensors work on the principle piezoelectricity which generation of charge takes place when diaphragm deflects due to applied acoustic pressure. Better sensitivity is achieved when the deflection is better which may be achieved by thinner diaphragm. But the linearity of the operation under more pressure and variation of the deflection of the diaphragm under the application of varying acoustic frequency are depending on the shape and dimensions.

The resonant acoustic sensors work on the principle similar to occurrence of resonance in RLC network. When acoustic pressure is guided though neck to the cavity, the acoustic pressure gets amplified and is much higher than the input pressure when the device is working under resonance [6]-[7]. The other side of the device can be constructed as a diaphragm and the deflection of the diaphragm can be converted into equivalent voltage through a piezoelectric layer deposited on the diaphragm. The conceptual diagram is as shown in fig.1.

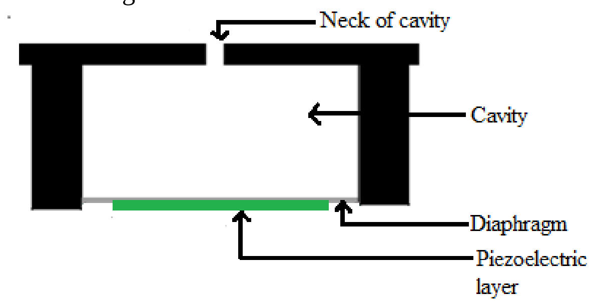


Fig.1. Conceptual Resonance based acoustic sensor.

The design of the diaphragm demands the dynamic parameters analysis of the structure like natural frequency, deflection and stress and strain distribution. Numerical methods like Finite Element Methods are very useful for the prediction of the physical systems' behavior when the phenomenon has more than one physics involved. The prediction is more realistic with initial conditions of stress/ strain and shape functions of the elastic element may be simulated [8]. The miniaturization of the structure is suggested due to the requirement of the source frequency in acoustic range and the natural frequency of the structure has to match with this for energy harvesting and should be at least three to five times highest applied frequency for sensing applications [9].

II. DESIGN OF THE DIAPHRAGM

The mechanical properties of the material used for diaphragm and the physical dimensions of the structure decide the sensitivity and frequency response of the acoustic pressure sensor [10]. The important parameters to be considered for acoustic signal sensing and acoustic energy harvesting for piezoelectric method are magnitude of the voltage generated and the natural frequency of the structure which are determined as dynamic response.

The proposed acoustic sensor structure is consisting of a Silicon diaphragm and the cavity is formed by back etching the silicon wafer. The piezoelectric layer sandwiched between two aluminum electrodes is deposited on the diaphragm. The structure is as shown in fig.2.

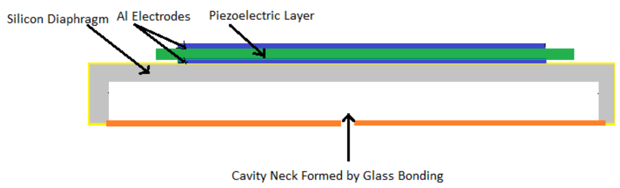


Fig.2. The structure with Silicon diaphragm and cavity with neck.

From fig.2, it is clear that the diaphragm being the key element converts the amplified acoustic pressure due to resonance into mechanical deflection and strass/strain which is further converted into electric potential by the piezoelectric layer deposited on the diaphragm.

The electric potential generated during piezoelectric phenomenon is given by the expression (1)

$$V = \frac{E d_{33}\, \mathcal{E} dA}{C} \quad (1)$$

Where ,

E is Young's modulus or Modulus of elasticity of the material in Pa.

d_{33} is the piezoelectric charge coefficient.

$\mathcal{E}$ is the applied strain.

dA is the area of the electrodes in m^2.

C is the capacitance of the structure in farad [9].

From (1), it is clear that the voltage generated depends on the strain applied to the diaphragm along with the material properties like Young's modulus and piezoelectric charge coefficient of the material. It also a dependent factor of area of the electrode within which piezoelectric layer is sandwiched and also the capacitance of the piezoelectric structure. Hence the diaphragm design should be done to get better strain and maximum deflection. Also in order to get better dynamic performance of the diaphragm, the shape and dimensions of the diaphragm are to be designed for the acoustic range of Sound Pressure Level (SPL) and frequency.

III. GEOMETRIC APPROACH OF DIAPHRAGM DESIGN

Simulation has been carried out for the dynamic performance analysis of diaphragm with different shapes that are practically feasible in MEMS fabrication like square, circular and rectangular. Further the dimensions like thickness and radius have been considered for analysis keeping in mind the practical fabrication feasibility. Finally, the entire structure with cavity as shown in fig.2 (Excluding Piezoelectric layer) has been simulated with and without neck understand the effect of cavity on the dynamic performance of the structure.

A. Shape of the diaphragm

In order to analyze the performance of different shapes of diaphragm, the dimensions are chosen in such a way that the total area exposed to the acoustic pressure is same for all the shapes. The stationary analysis is carried out to understand the deflection, stress and strain range for unidirectional value and dynamic analysis is carried out to analyze the natural frequency, modal frequency and variation of displacement with respect to the variation of frequency.

i. Square

The side length of square shaped diaphragm is assumed to be $\sqrt{\pi a}$. All the sides of the diaphragm are hinged and the pressure of 1 Pa is applied on the plain surface of the diaphragm from downwards so that the deflection and stress/ strain destitution can be understood. This detail is further utilized to decide the area of depositing the piezoelectric material. The dynamic performance was carried out by Eigen frequency study and frequency domain study with input pressure 1 Pa applied from bottom and frequency range from 100 Hz to 100 KHz taking into consideration first six Eigen frequencies.

a. Stationary Performance

The maximum deflection for the given pressure is given by (2).

$$W_{max} = \frac{0.0133 P_a^2}{E h^3} \quad (2)$$

The maximum stress is given by (3),

$$\sigma_{max} = \frac{0.309\, P_a^2}{h^2} \quad (3)$$

Where,

P is the pressure in N/m^2

a is side length in μm

h is the diaphragm thickness in μm.

E is the Modulus of elasticity in Pa.

The simulated results for square shaped diaphragm having side length 5317.7 μm and thickness 30 μm are as shown in fig.3. The diaphragm deflection, displacement, stress and strain along line passing through the centre are as shown in fig.3.a, 3.b. 3.c and 3.d.

b. Dynamic Performance

The dynamic performance of the square shaped diaphragm is as shown in fig.4. The Fourth modal frequency displacement, displacement for all modal frequencies, frequency vs displacement for first modal frequency and frequency vs displacement for first and second major frequencies are as shown in fig.4.a,4.b, 4.c and 4.d.

ii. Circular

The radius of circular shaped diaphragm is assumed to be *a*. All the sides of the diaphragm are hinged and the pressure of 1 Pa is applied on the plain surface of the diaphragm from downwards so that the deflection and stress/ strain destitution can be understood. This detail is further utilized to decide the area of depositing the piezoelectric material. The dynamic performance was carried out by Eigen frequency study and frequency domain study with input pressure 1 Pa applied from bottom and frequency range from 100 Hz to 100 KHz taking into consideration first six Eigen frequencies.

a. Stationary Performance

The maximum deflection is given by (4).

$$W_{max} = \frac{3PR_0^2}{16\, t^2\, E}\left(1 - v^2\right) \qquad (4)$$

The maximum stress is given by (5),

$$\sigma_{max} = \frac{1.25\, PR_0^4}{t^2} \qquad (5)$$

Where,

P is the pressure in N/m^2
R_0 is the diaphragm radius in µm
t is the diaphragm thickness in µm
v is Poisons ratio (unit less)
E is the Modulus of elasticity in Pa [11].

The simulated results of circular diaphragm having radius 3000 µm and thickness 30 µm are as shown in fig.5. The diaphragm deflection, displacement, stress and strain along line passing through the centre are as shown in fig.5.a, 5.b. 5.c and 5.d.

b. Dynamic Performance

The undamped natural frequency of circular diaphragm is given by the expression (6).

$$\frac{0.469t}{R_0^2}\sqrt{\frac{E}{\rho(1-v^2)}} \qquad (6)$$

Where,

t is the thickness of the diaphragm in µm.
E is the Young's Modulus or Modulus of elasticity of the material in Pa.
v is the Poison's ratio
R_0 is the radius of the diaphragm in µm.
ρ density of the material in kg/m^3 [12].

iii. Rectangular

The dimensions of the rectangular diaphragm is assumed to be width $(\pi/2)a$ and length $2a$. All the sides of the diaphragm are hinged and the pressure of 1 Pa is applied on the plain surface of the diaphragm from downwards so that the deflection and stress/ strain destitution can be understood. This detail is further utilized to decide the area of depositing the piezoelectric material. The dynamic performance was carried out by Eigen frequency study and frequency domain study with input pressure 1 Pa applied from bottom and frequency range from 100 Hz to 100 KHz taking into consideration first six Eigen frequencies.

a. Stationary Performance

The maximum deflection for the given pressure is given by (7).

$$W_{max} = \frac{0.0133\, P\, ab}{E\, h^3} \qquad (7)$$

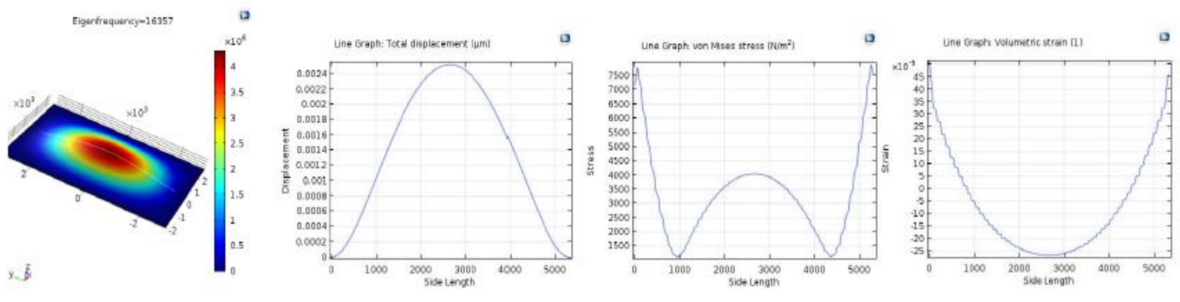
The maximum stress in the middle of each edge is given by (8)

$$\sigma_{max} = \frac{0.309P^2}{h^2} \qquad (8)$$

Where,

P is the pressure in N/m^2
a and b are side lengths in µm
h is the diaphragm thickness in µm.
E is the Modulus of elasticity in Pa.

The simulated results for rectangular shaped diaphragm having side lengths 4712.4 µm X 6000 µm and thickness 30 µm are as shown in fig.7. The diaphragm deflection, displacement, stress and strain along line passing through the center are as shown in fig.7.a, 7.b. 7.c and 7.d.



a. b. c. d.

Fig.3.a) Square diaphragm deflection b) Deflection c) Stress d) Strain.

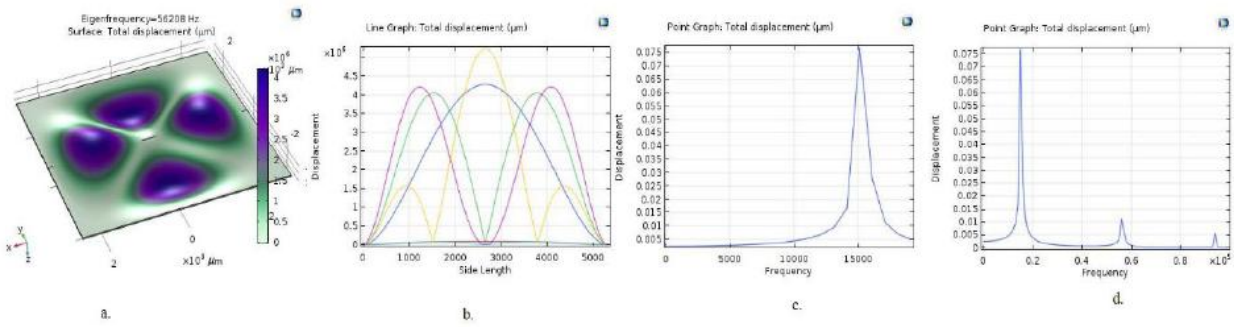


Fig.4.a) Fourth modal frequency displacement b) Displacement for all modal frequencies c) Frequency vs Displacement for first modal frequency d) Frequency vs Displacement for first and second major frequencies.

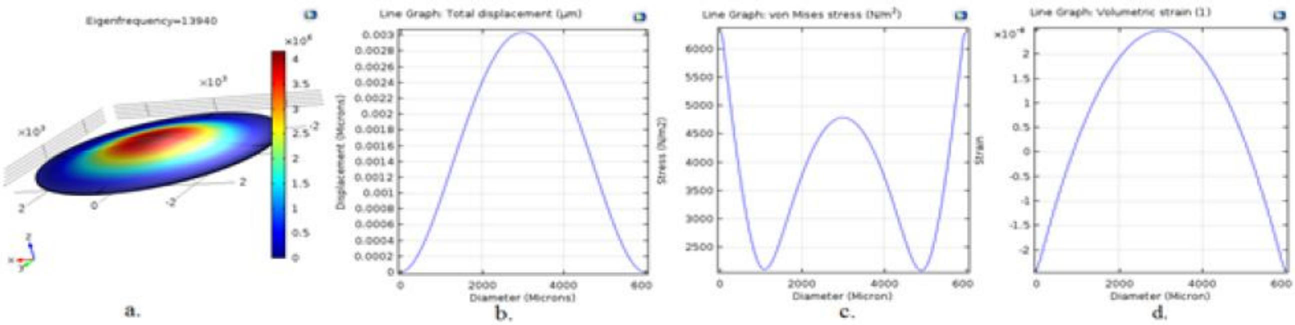


Fig.5.a) Circular diaphragm deflection b) Deflection c) Stress d) Strain.

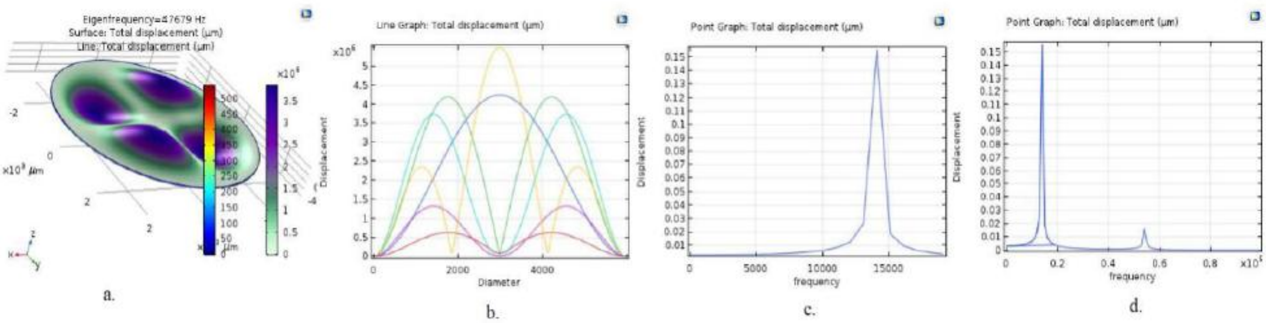


Fig.6.a) Fourth modal frequency displacement b) Displacement for all modal frequencies c) Frequency vs Displacement for first modal frequency d) Frequency vs Displacement for first and second major frequencies.

b. Dynamic Performance

The dynamic performance of a rectangular diaphragm is as shown in fig.8. The Fourth modal frequency displacement, displacement for all modal frequencies, frequency vs displacement for first modal frequency and frequency vs displacement for first and second major frequencies are as shown in fig.8.a,8.b, 8.c and 8.d.

A comparison table of all the three feasible major shapes viz. Square, circular and rectangular is as shown in Table-I

From Table-I and the above analysis, the following conclusion is drawn.

i. The maximum centre deflection happens in circular diaphragm. However, the range of stress at the edges is found to be less in circular diaphragm. The maximum range of unidirectional stress and strain is available for circular diaphragm which is useful for deposition of piezoelectric material in that range.

ii. The natural frequency being one of the important factors in diaphragm design for acoustic applications, circular diaphragm has least value of first mode of vibration frequency [13].

From the above conclusions, it can be derived that the circular diaphragm was chosen over the other shapes for the pressure sensing and energy harvesting applications.

Further, according to (6), the radius and the thickness of the diaphragm are also important factors which decide the natural frequency. Hence, the analysis of these parameters has also been carried out.

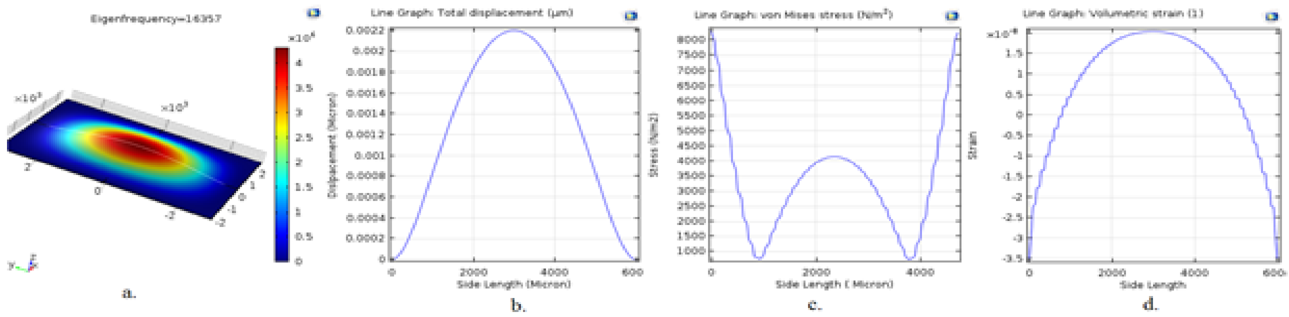


Fig.7.a) Rectangular diaphragm deflection b) Deflection c) Stress d) Strain.

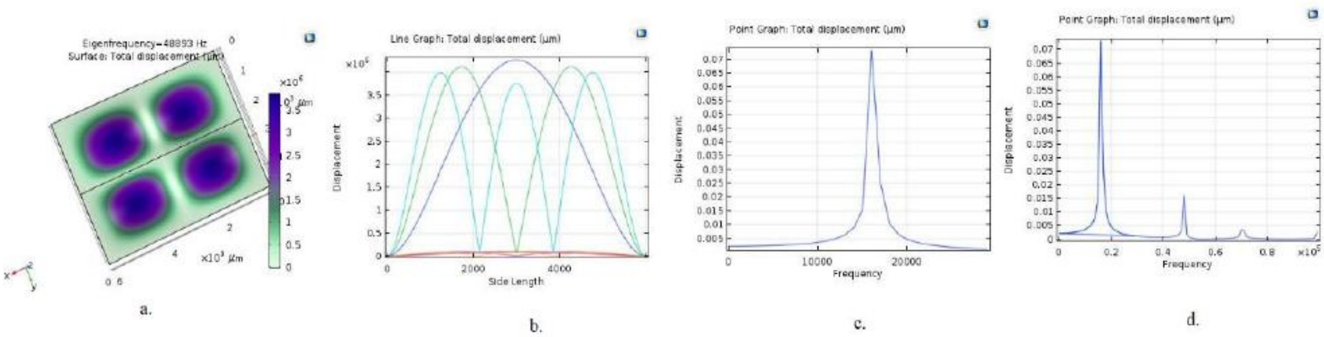


Fig.6.a) Fourth modal frequency displacement b) Displacement for all modal frequencies c) Frequency vs Displacement for first modal frequency d) Frequency vs Displacement for first and second major frequencies.

Table-I. Comparison Table of different shapes of diaphragm.

Shape	Dimension (µm)	Maximum Displacement(µm)	Natural Frequency (Hz)	Maximum Stress(N/m^2)	Maximum Strain
Square	5317.7 (Side length)	0.0024	15652	7500(Tensile) 4000(Compressive)	2.3X10^{-8}
Circular	3000 (Radius)	0.003	13940	6300 (Tensile) 4800 (Compressive)	2.5 X10^{-8}
Rectangular	4712.4X 6000	0.0022	16357	8500 (Tensile) 4000(Compressive)	2.0 X10^{-8}

B. Radius of the diaphragm

The silicon circular diaphragm of thickness 30 µm is analyzed for different diameter. The eigen frequency study has been carried out to tabulate the natural frequency of the structure. The simulated structures with radius varying from 500 µm to 4000µm are as shown in fig 7.a,7.b,7.c,7.d and 7.e respectively.

From (6), it is clear that the natural frequency of the structure is inversely proportional to the square of the radius of the circular diaphragm. The simulated results are tabulated in Table-II.

Table-II. Radius vs natural frequency for circular diaphragm.

Sl.No.	Radius (µm)	Frequency (Hz)
1.	500	501100
2.	1000	125500
3.	2000	31367
4.	3000	10809
5.	4000	6805

From Table-II, it is clear that the circular diaphragm of radius 3000 µm to 4000 µm is suited for acoustic frequency range.

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However, the radius 4000 µm and above may lead to fabrication difficulty like stiction due to large area and small thickness during back etching of the structure. Hence circular diaphragm of radius 3000 µm has been selected for design.

C. Thickness of the diaphragm

The thickness of the diaphragm is another major parameter affecting the natural frequency. Hence, the silicon circular diaphragm of radius 3000 µm is analyzed for different thickness. The eigen frequency study has been carried out to tabulate the natural frequency of the structure. The simulated structures with thickness varying from 10 µm to 40µm are as shown in fig 8.a,8.b,8.c,8.d and 8.e respectively.

From (6), it is clear that the natural frequency of the structure is directly proportional to the square of the radius of the circular diaphragm. The simulated results are tabulated in Table-III.

Table III. Thickness vs natural frequency for a circular diaphragm.

Sl.No.	Thickness (µm)	Frequency (Hz)
1.	10	3603.9
2.	20	7206.8
3.	25	9007.9
4.	30	10809
5.	40	14411

From Table-III, it is clear that the circular diaphragm of thickness 30 µm is suited for acoustic frequency range.

IV. STRUCTURE ANALYSIS

The final proposed structure has been simulated with 30 µm thick and 3000 µm radius diaphragm and upon which a piezoelectric layer of 1 µm sandwiched between two Aluminum electrodes of 300 nm. The cavity has been formed by back etching the silicon wafer by a depth of 300 µm. The dimensions are chosen keeping in mind the structure fabrication feasibility. The structure has been simulated without cavity neck and with cavity neck of variable radius.

A. Structure with open cavity (Without neck)

The simulation of the structure with open cavity is as shown in fig.9. The analysis study has been done by Eigen frequency study and frequency domain study. The Surface displacement at natural frequency, the displacement at frequency variation up to 100 kHz and Surface displacement and Eigen frequency for second modal frequency is as shown in fig 9.a, 9.b and 9.c respectively.

B. Structure with cavity Neck.

The simulation of the structure with cavity neck of radius 750µm is as shown in fig.10. The analysis study has been done by Eigen frequency study and frequency domain study. The surface displacement at natural frequency, the displacement at frequency variation up to 100 kHz and surface displacement and Eigen frequency for second modal frequency is as shown in fig 10.a, 10.b and 10.c respectively. The first modal frequency and displacement ranges for structure with open cavity and that with cavity neck of 1500 µm diameter is as shown in fig. 11.a and 11.b respectively.

From fig.11, it is clear that the pressure amplification due to resonance is better with cavity neck due to which the displacement of 0.28 µm and also the first modal frequency is less with cavity neck (11.076 kHz). The bandwidth is better with cavity neck as compared to open cavity as shown.

V. CONCLUSION

The design analysis of diaphragm that can be used for piezoelectric acoustic sensor has been designed and simulated for stationary and dynamic performance analysis. At first, the shape of the diaphragm is analyzed keeping the area applied to the pressure constant. It is found that the circular diaphragm has better response as compared to the other conventional shapes. Further the radius and thickness of the diaphragm are analyzed to match the acoustic frequency range. It has been found that the circular diaphragm having radius 3000 µm and thickness 30 µm has fabrication feasibility and the natural frequency in acoustic range.

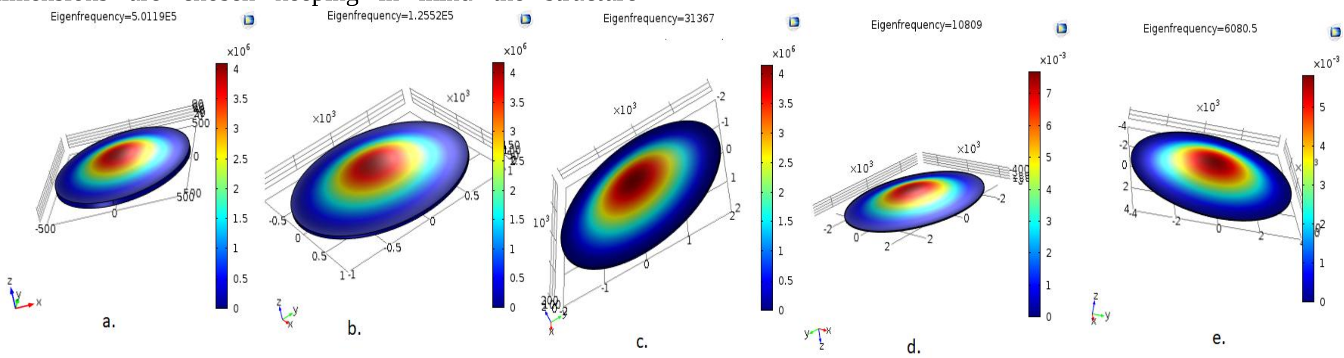

Fig.7.Simulated Eigen frequency study of a circular diaphragm with radius a)500 µm b)1000 µm c) 2000 µm d)3000 µm e) 4000 µm.

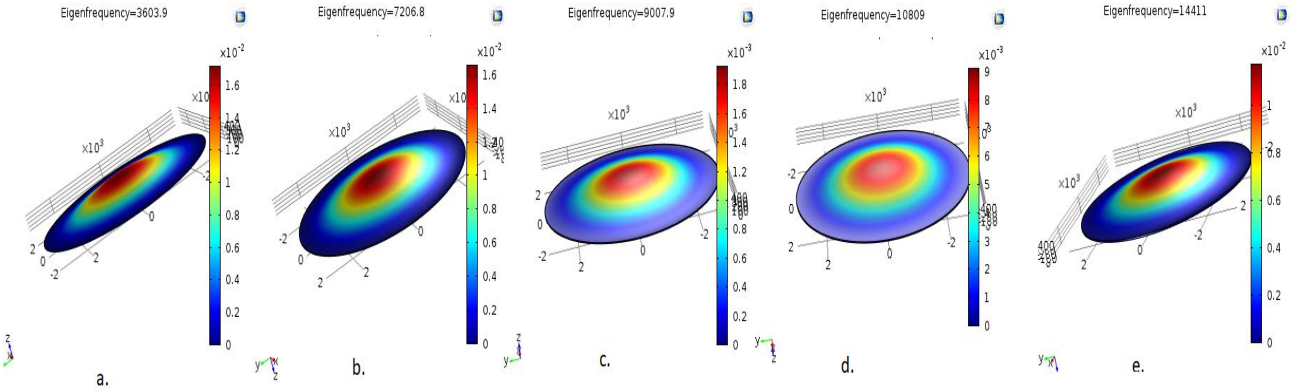

Fig.8.Simulated Eigen frequency study of a circular diaphragm with thickness a)10 µm b)20 µm c) 25 µm d)30 µm e) 40 µm.

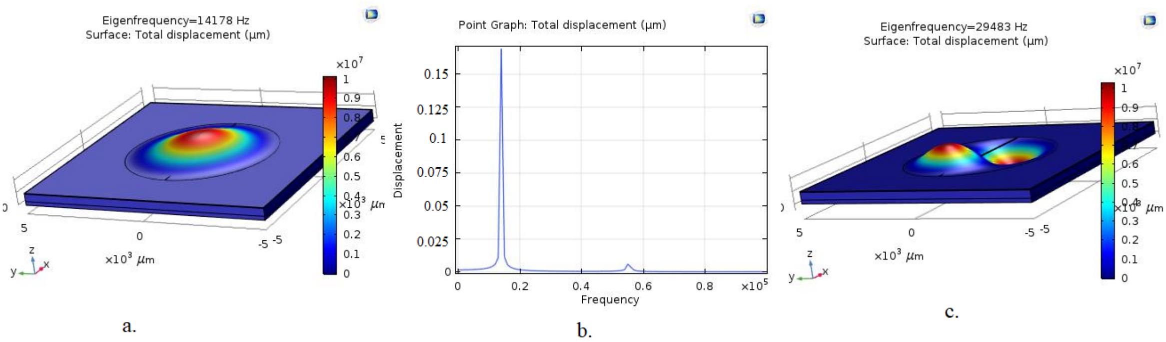

Fig.9. Structure without cavity neck. a) Surface displacement and Eigen frequency for natural frequency b) Frequency vs displacement c) Surface displacement and Eigen frequency for second modal frequency.

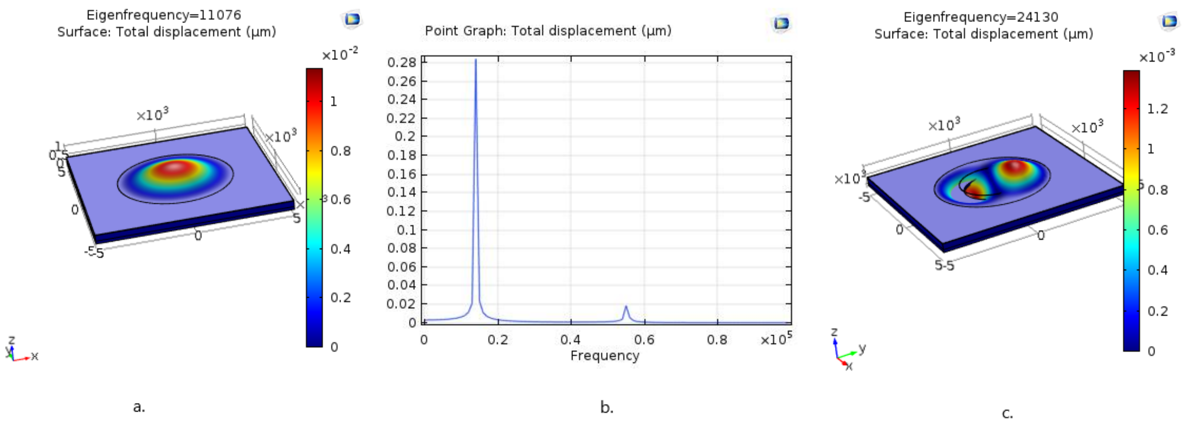

Fig.10. Structure with cavity neck. a) Surface displacement and Eigen frequency for natural frequency b) Frequency vs displacement c) Surface displacement and Eigen frequency for second modal frequency.

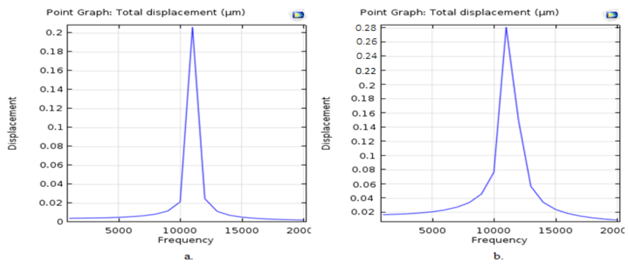

Fig.11. Frequency vs displacement graph. a) with open cavity b) with cavity having neck of 1500 µm diameter.

These dimensions are further utilized to design the complete sensor structure with cavity. The analyses are also done to understand the effect of cavity neck on the dynamic response. From the simulation, it was observed that the deflection was better for the structure with cavity neck of diameter 1500 µm due to amplification of pressure during resonance. All the dimensions of the structure are designed to make the fabrication of the device feasible.

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