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Modeling, Simulation and Performance Analysis of Multichannel Mems Piezoelectric Cantilevers for Cochlear Implantable Module

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Abstract

This work presents the enhanced area-efficient Multi-channel MEMS (Micro-Electrical Mechanical System) piezoelectric cantilever device (PCD) for a fully cochlear implantable sensor that works within the audible frequency range of 300-4800 Hz. The sound pressure level (SPL) of 95 dB, 100 dB, and 110 dB input is given in order to resonates the audible frequency range of the device which is placed on the eardrum. This stimulates the auditory nerve via the cochlea to send information to the brain. As a result, the Multi-channel MEMS piezoelectric cantilever device generates the highest potential voltage of 870 mV at 110-dB SPL and is detected under the excitation of 300 Hz. The output parameters such as von Mises stress, displacement, and the complete frequency bandwidth performance are analyzed using COMSOL Multiphysics.

Key-words: Micro-Electrical Mechanical System (MEMS), Piezoelectric Cantilever, Bandwidth, Potential Voltage, Fully Cochlear Implantable Sensor.

1. Introduction

According to the “Global Hearing Implants Market Outlook 2020 report”, the hearing implants market is estimated to reach US$ 2.9 Billion by 2020. At present, the cochlear implants occupy the largest share, and it tends to maintain its position in the upcoming years [1]. The human

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hearing frequency range varies from 20 Hz to 200 kHz, although human speech frequency ranges from 250 Hz to 8000 Hz. Formerly, hearing aids were used as desired treatment option for hearing loss but some patients do not benefit from it due to its drawbacks. The social stigma of wearing conventional hearing aids made some patients deprive of courage [2]. In isolation, this made increased acceptance to introduce another alternative option in the form of hearing implants which are also called Middle ear implants (MEIs) or Cochlear implants (CIs) [3]. Cochlear Implant is a small electronic device that provides a sense of sound to a person who has profound or severe nerve deafness. The cochlear implant consists of a speech processor, receiver-stimulator and electrode array. Sound enters into the microphone, the processor picks the sound from the microphone and sends it to the stimulator which is placed under the skin. The sound signals are converted to electric impulses by the stimulator. The electrode array collects the signals from the stimulator through the cochlea and passes them to the brain. Cochlear Implants have some complications such as wound, infection, fluid leak, device failure, balance issue and nerve injury [4]. In recent years, MEMS technology plays the challenging task to design and fabricate tiny integrated devices for implantable sensors. MEMS Implantable sensors have various advantages such as small package size, low cost, lightweight, low power consumption, high complexity, higher output signal, etc [5]. Here, MEMS cochlear implantable hearing aids were made in advancement on piezoresistive, capacitive, and piezoelectric sensors. The piezoresistive and capacitive sensors had surgical risk, high power consumption, and need supporting ends on the sensor. To overcomes these limitations, we proposed MEMS piezoelectric fully implantable sensor. Piezoelectric sensors generate electric potential voltage, when the pressure is applied to the load, and the sensor gets charged by itself. It doesn’t need any additional power source for the sensor element. The main advantage while designing the fully cochlear implantable sensor with low power consumption [6]. In existing MEMS piezoelectric acoustic sensor with eight cantilever beam is designed and simulated by input sound pressure level (SPL) of 110 dB and the electric potential voltage of 870 mV were generated for the fully cochlear implantable sensor.

In this paper, we proposed an enhanced area-efficient multi-channel MEMS piezoelectric cantilever for a fully cochlear implantable sensor. The multi-channel MEMS piezoelectric cantilever module is placed on the eardrum to sense the incoming sound. The design consists of sixteen cantilever beams that are connected in parallel to make a more enhanced and compact size within the device. The input SPL of 110 dB is given and the high potential voltage of 870 mV is generated. The cantilever beam deflects with the reference of particular speech frequency within the bandwidth of 300 Hz to 4800 Hz. The output parameters such as electric potential voltage, von Mises stress, displacement, and bandwidth are obtained and its performance had been analyzed by using COMSOL Multiphysics.

2. Sensor Design

2.1. Cantilever Beam

Zinc oxide (ZnO) is chosen as upper most layer because of its excellent piezoelectric coefficients and coefficient of electromechanical transformation are relatively high when compared to other piezoelectric materials. The polysilicon is chosen as the bottom most layer as the substrate [7]. The length of the cantilever beam varies from 5300 µm to 1344 µm, the width of 200 µm and the thickness of 5 µm of the cantilever beam are kept constant is shown in the figure 1. The physical properties of zinc oxide material are deformed with the Young's modulus of 161GPa, a poisson's ratio of 0.35, and a density of 5680kg/m^3, and poly-silicon material with the Young's modulus of 160GPa, a poisson's ratio of 0.22, and a density of 2320kg/m^3.The materials are bonded together along with the X, Y and Z-axis. Where E_s, E_p are the Young's moduli and the t_s, t_p are the thickness of the nonpiezoeletric and piezoelectric materials. Schematic view of piezoelectric cantilever beam is shown in the figure 2. Considering the pressure P is applied to the upper surface of the ZnO oxide. The frequency varies from 300-4800 Hz with respect to the different length of the cantilever beams.

Figure 1 - Frequency Vs Length of the Beam

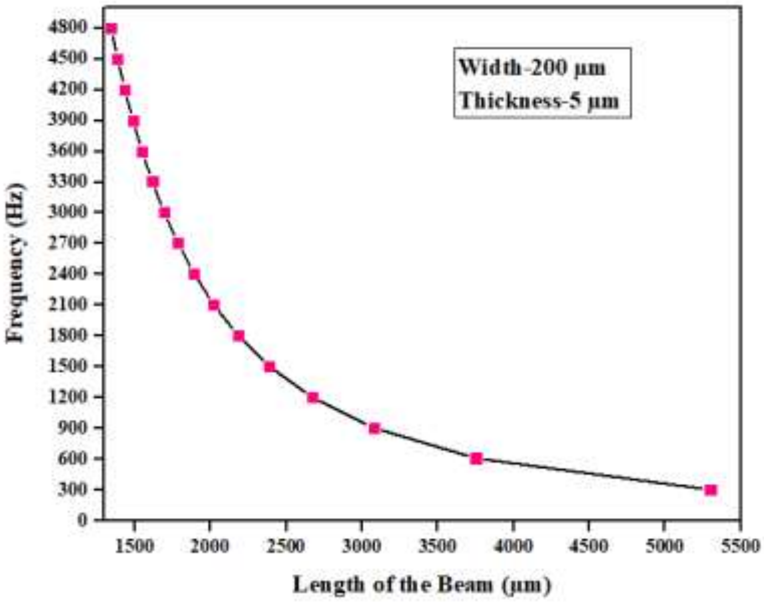

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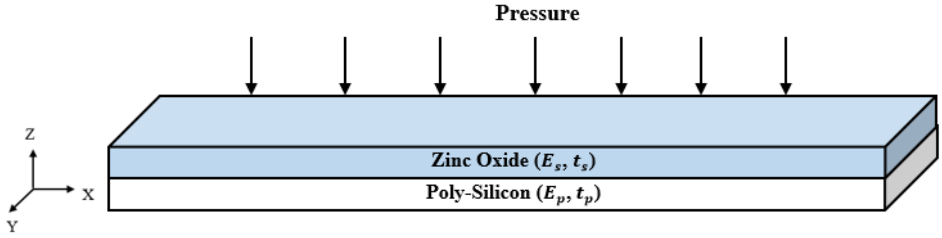
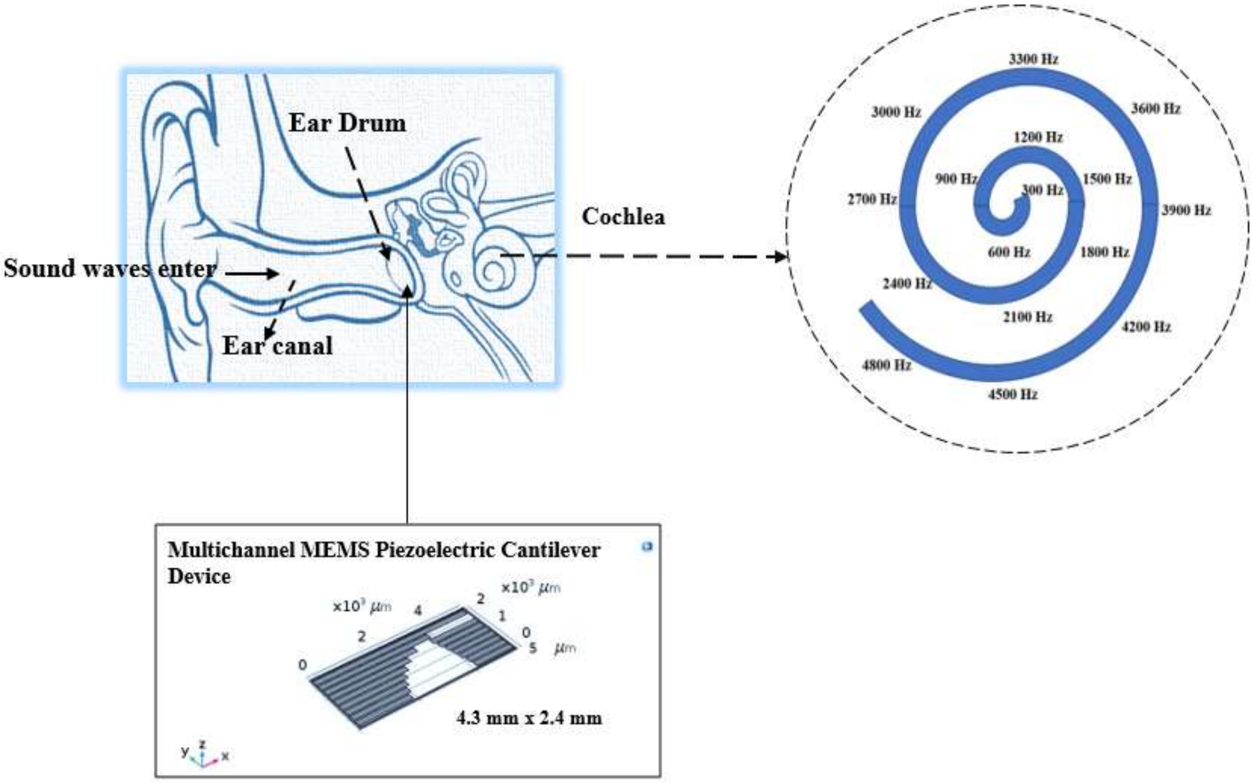
Figure 2 - Schematic View of Piezoelectric Cantilever Beam



2.2. Design of the Multichannel MEMS Piezoelectric Cantilever Device

The proposed Multichannel MEMS PCD enhanced area efficient of 4.3×2.4 mm is developed with several cantilever beams with different frequencies. The device is implanted to the middle ear, more exactly to the inner side of the ear drum which consists of sixteen cantilever beams distributed linearly and parallel to each other [8]. An acoustic sound Pressure Level of 95 dB,100 dB and 110 dB impinges on the eardrum; the device starts to vibrate. The vibration triggers the cantilever beams with the resonance frequency matches with the excitation frequency in cochlea starts to resonate within the hearing bandwidth of 250 to 4800 Hz. The triggered beam produces the electric potential voltage significantly higher than the other cantilever beams. The generated electric potential stimulates the nerves and sends information to the brain [9].

Figure 3 - Schematic Structure of Proposed System



3. Mathematical Models

3.1. Displacement Modelling and Frequency Response Analysis

The beam deflects in the z-direction due to pressure is applied as boundary load. Therefore, electric potential voltage is induced and thereby stress or strain is produced the inverse of the radius of curvature(r) can be expressed as shown in the below equation 1 [10].

$$\frac{1}{r} = \frac{d^2h(x)}{dx^2} = \frac{M(x)}{WD_1} = -\frac{F}{WD_1}[L-x] \qquad (1)$$

The x values varies from 0< x<L, where $h(x)$=Axial Displacement,$M(x)$=Bending moment of the cantilever, D_1=Bending Modulus per unit width can be expressed as equation 2.

$$D_1 = \frac{E_s^2t_s^4+E_p^2t_p^4+2E_sE_pt_st_p+(2t_s^2+2t_p^2+3t_st_p)}{12(E_st_s+E_pt_p)} \qquad (2)$$

where, E_s and E_p are the Young’s Modulus and the parameters $t_s$and t_p are the thickness of the polysilicon and piezoelectric layers. Equation 3 shows to calculate the boundary condition of the axial and tip displacement. Initially the axial displacement and its first derivation is kept at zero on its fixed end [11]. This can be written as

$$h_{(x=0)} = 0 \; and \; \left.\frac{dh}{dx}\right|_{x=0} = 0 \qquad (3)$$

The axial displacement is obtained by applying the below boundary condition. By integrating (1), we get

$$\frac{dh}{dx} = -\int \frac{F}{2WD_1}[L-x]^2 d \qquad (4)$$

$$\frac{dh}{dx} = -\frac{F}{2WD_1}\left[L^2\,x - 2L\frac{x^2}{2} + \frac{x^3}{3}\right] + K_1 \qquad (5)$$

$$h = -\frac{F}{2WD_1}\left[L^2\,\frac{x^2}{2} - L\frac{x^3}{3} + \frac{x^4}{12}\right] + K_2 \qquad (6)$$

$$h_{tip} = -\frac{F}{WD_1}\left[\frac{L^4}{8}\right] \qquad (7)$$

In equation 8, W & L are width and length of the polysilicon substrate and Force F in terms of pressure P is applied in Pascal (Pa). Stiffness constant(k) of the beam is defined as the force required for unit tip displacement can be derived from equation (8).

$$k=\frac{Fa}{h_{tip}} = \frac{8WD_1}{L^3} \qquad (8)$$

The audible hearing frequency range from 300 to 4800 Hz is calculated manually by equation 10,11. The calculated frequency is matches with the simulated frequency using COMSOL Multiphysics shown in the figure 6 a.

$$S_{d1} = \frac{2}{3}\frac{Wt_{seq}e_{31}}{W_n^2} \tag{9}$$

$$K = \frac{8WD_1}{L^3}\ and\ W_n = \sqrt{\frac{K}{M}} \tag{10}$$

$$F = \frac{1}{2\pi}\sqrt{\frac{K}{M}} \tag{11}$$

3.2 Material Properties

Piezoelectric material produces electrical charge when it is mechanically deformed. Most of the materials the data appears in stress-charge form can be easily transform into COMSOL Multiphysics software. The following equations written in the stress-charge format.

$$\mathrm{T} = \mathrm{C_E S} + \mathrm{eE} \tag{12}$$

$$\mathrm{D} = \mathrm{e^T S} + \mathrm{\varepsilon_s E} \tag{13}$$

Where S is the strain vector; T is the stress vector; D is the electric flux density vector; E is the electric field vector; $\mathbf{C_E}$ is the elasticity matrix; e is the piezoelectric stress matrix; $\boldsymbol{\varepsilon}_\mathbf{s}$ is the dielectric matrix. ZnO is carefully chosen as piezoelectric material and its standard elasticity matrix(C_E), the relative permittivity matrix(ε_{rs}) are used in COMSOL Multiphysics.

$$C_E = \begin{bmatrix} 209 & 121.1 & 105 & 0 & 0 & 0 \\ 0 & 209 & 105 & 0 & 0 & 0 \\ 0 & 0 & 211 & 0 & 0 & 0 \\ 0 & 0 & 0 & 42.3 & 0 & 0 \\ 0 & 0 & 0 & 0 & 42.3 & 0 \\ 0 & 0 & 0 & 0 & 0 & 44.2 \end{bmatrix} [GPa]$$

$$e_{ES} = \begin{bmatrix} 0 & 0 & -0.567 \\ 0 & 0 & -0.567 \\ 0 & 0 & 1.032 \\ 0 & 0 & 0 \\ 0 & -0.480 & 0 \\ -0.480 & 0 & 0 \end{bmatrix} [C/m^2]$$

$$\varepsilon_{rs} = \begin{bmatrix} 8.546 & 0 & 0 \\ 0 & 8.546 & 0 \\ 0 & 0 & 10.204 \end{bmatrix} [F/m]$$

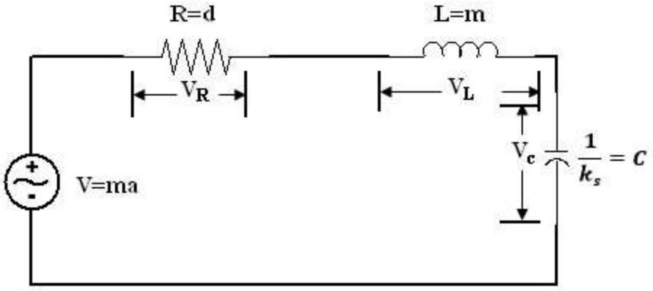
3.3 Sound Pressure and Sound Pressure Level

Sound pressure is the pressure measured within the wave relative to the ambient air pressure. Quiet sounds produce sound waves with small sound pressures whereas loud sounds produce sound waves with large sound pressures. Sound pressure level is measured in decibels (dB) and can be calculated using the following equation, where p is the sound pressure of the sound wave and p_0 is the reference sound pressure.

$$L_P = 20\ log_{10}\left(\frac{p}{p_0}\right) dB \qquad (14)$$

3.4 Equivalent Circuit and Bandwidth

Figure 4 - Equivalent Circuit of the Piezoelectric Cantilever Beam



In an R-L-C circuit the current and voltage are related by the equation

$$V = L\frac{di}{dt} + \frac{1}{c}\int idt + iR \qquad (15)$$

If i=$\frac{dz}{dt}$, (15) can be rewritten as

$$ma = \frac{di}{dt} + K_s \int idt + (d + d_e)i. \qquad (16)$$

From comparison of (40) and (41), it is true that

$$V = ma$$

$$L = m$$

$$K_s = \frac{1}{c}$$

or $c = \frac{1}{K_s}$, (17)

$$R = d + d_e$$

The damping constant “d” is calculated using the relationship

$$d = 2m\omega_n\zeta$$

By substituting, $\omega_n = 2\pi f_0$ and “ζ" is the damping ratio.

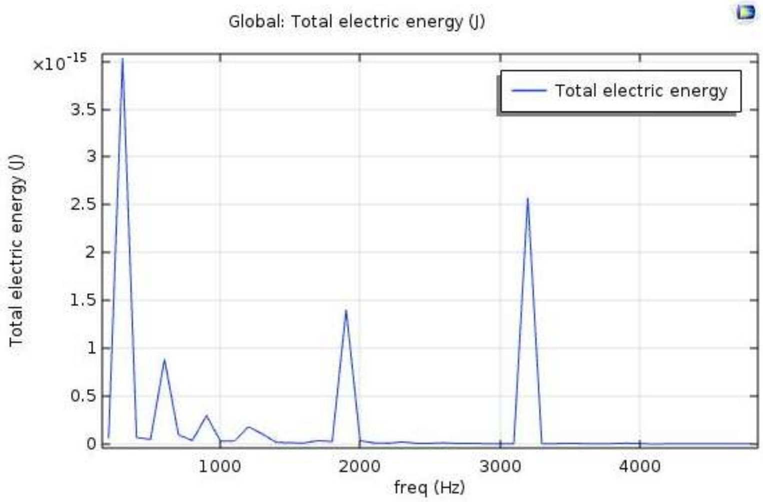
In order to get the displacement at various frequencies of Multi-channel piezoelectric cantilever device for a fully cochlear implantable sensor, the following method is implemented. The current flowing through this circuit will be equal to $\frac{dz}{dt}$. The measurement of current will gives the velocity $\frac{dz}{dt}$. But the required quantity is the since i=$\frac{dz}{dt}$.The voltage (Vc) is then multiplied by value of “C” to directly get the displacement [12]. The parameters of R, L, C and source voltage are summarized in table 1.

Table 1 - Parameters of Equivalent Electrical Circuit

Frequencies (Hz)	**Source voltage (mV)**	**Resistance (R) in (mΩ)**	**Inductor (L) in mH**	**Capacitance (C) in F**
300	4.240e-8	2.636e-6	4.159e-7	6.337
600	2.943e-7	6.606e-7	3.000e-8	2.244
900	2.416e-7	3.002e-7	2.463e-8	1.242
1200	2.095e-7	1.695e-7	2.135e-8	0.809
1500	1.874e-7	1.086e-7	1.910e-8	0.579
1800	1.711e-7	7.544e-8	1.744e-8	0.440
2100	1.586e-7	5.573e-8	1.617e-8	0.351
2400	1.483e-7	4.262e-8	1.512e-8	0.287
2700	1.400e-7	3.384e-8	1.427e-8	0.241
3000	1.329e-7	2.744e-8	1.354e-8	0.206
3300	1.267e-7	2.272e-8	1.292e-8	0.179
3600	1.215e-7	1.918e-8	1.238e-8	0.157
3900	1.168e-7	1.638e-8	1.190e-8	0.140
4200	1.125e-7	1.143e-8	1.147e-8	0.125
4500	1.088e-7	1.233e-8	1.109e-8	0.113
4800	1.055e-7	1.090e-8	1.075e-8	0.103

By calculating the equivalent resistances R, L and C for all the sixteen piezoelectric cantilever beams is simulated by using COMSOL Multiphysics and the complete bandwidth of 300-4800 Hz peak plot is obtained as shown in figure.

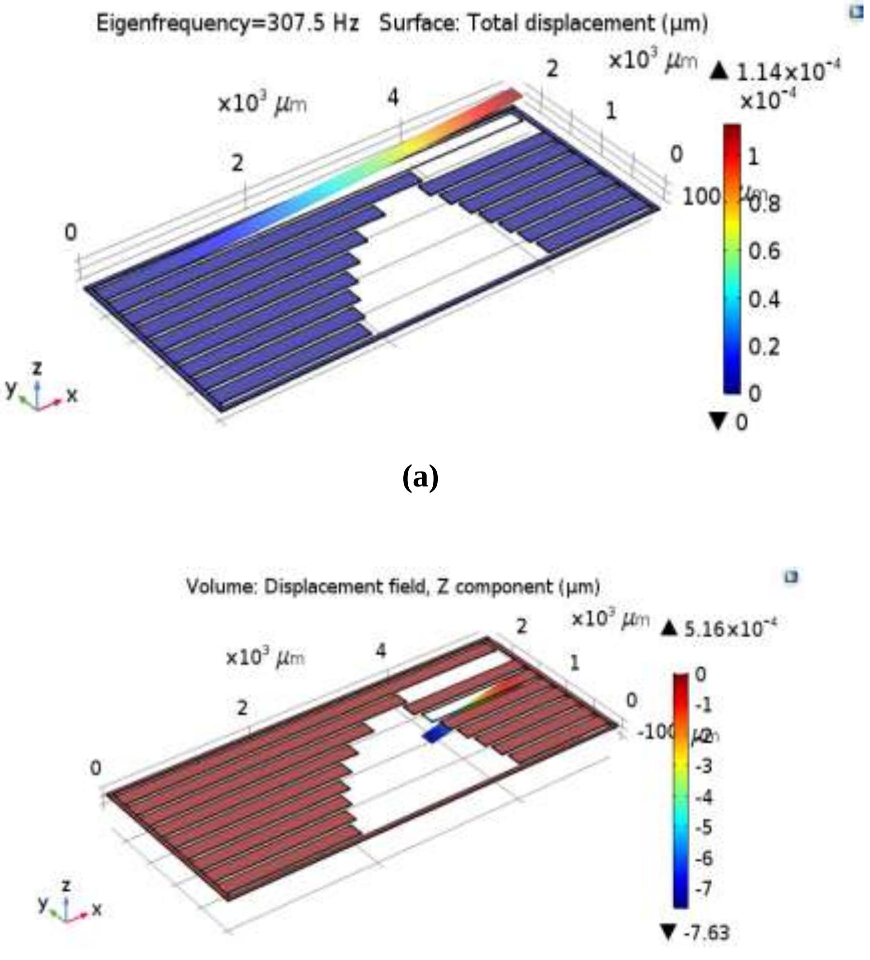
Figure 5 - Bandwidth Coverage for Audible Frequency Range



4. Simulation Results

The proposed Multichannel MEMS PCD of sixteen cantilevers in a linear arrangement was simulated in COMSOL Multiphysics and the results are shown in figure 5 and figure 6. The input SPL is simulated distinctly for 95 dB, 100 dB, 110 dB for 300-4800 Hz resonant frequencies. The main purpose of this device is to produce the maximum electric potential voltage of 180mV at 300 Hz for a sound pressure level of 110dB. Figure 6 a and b shows the Eigen frequency and displacement of $5.16 \times 10^{-4} \mu m$ on the Z component are simulated for 300 Hz. Figure 7 and figure 8 shows the output performance analysis of von Mises stress(N/m^2), eigen frequency(Hz), displacement(μm), the electric potential voltage(mV/Pa) and bandwidth.

Figure 6 a and b - Eigen Frequency and Displacement of the Cantilever Beam at 300 Hz



(a)

(b)

Sixteen resonant frequencies from 300 to 4800 Hz with the maximum displacement, voltage and von mises stress plots are generated using COMSOL Multiphysics.

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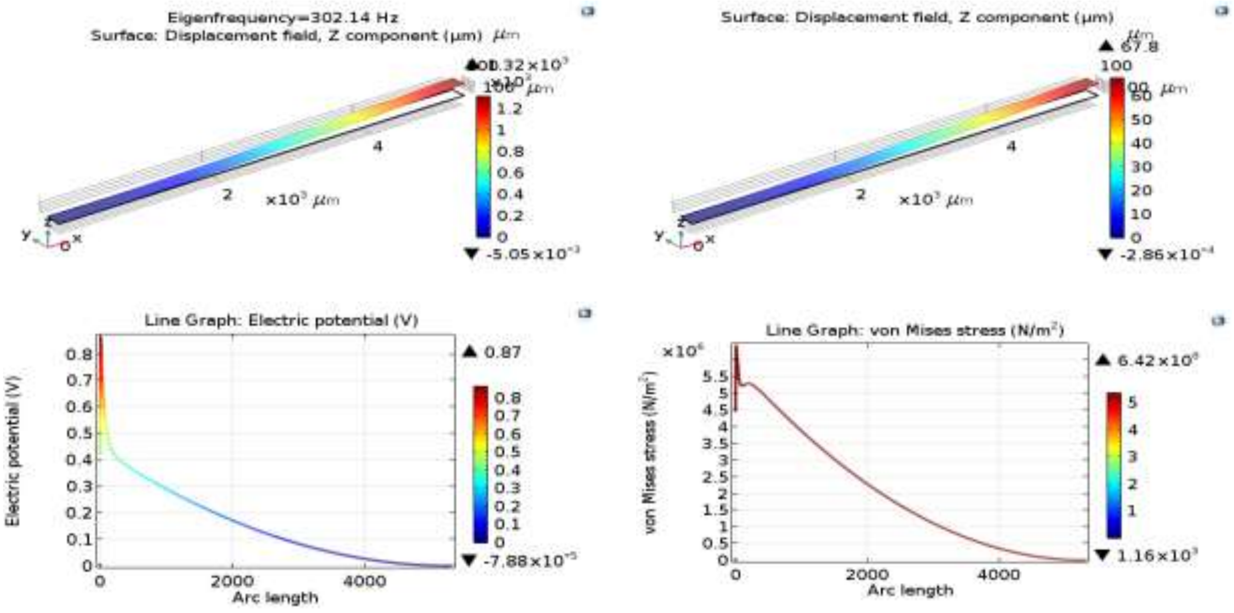
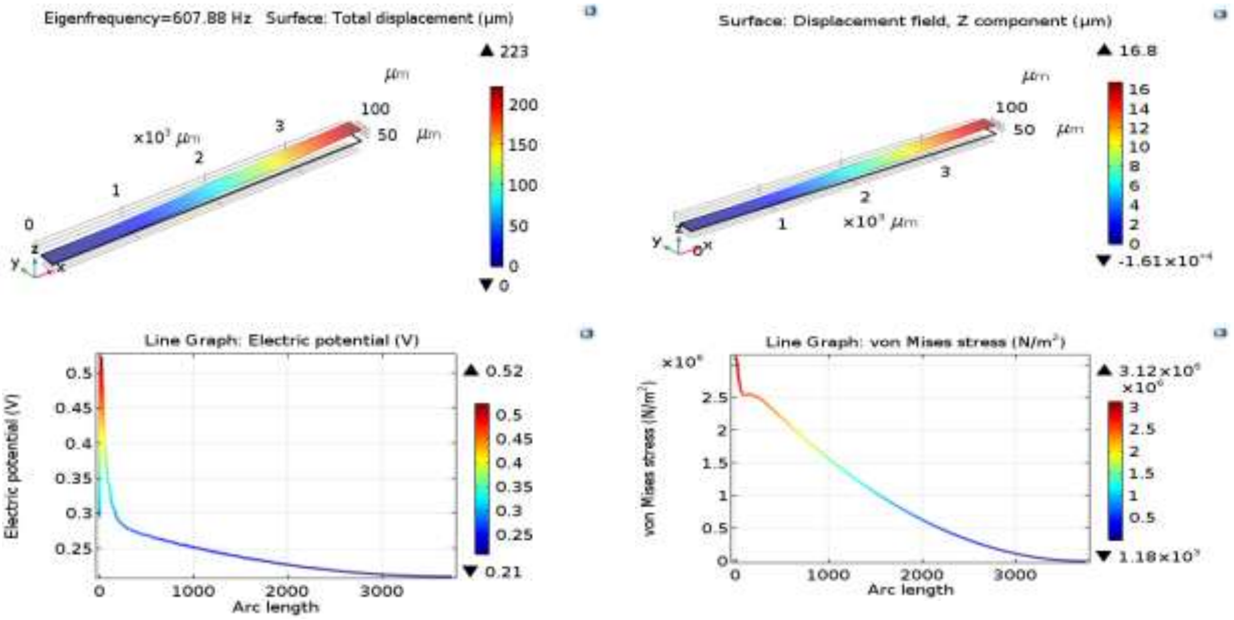
Figure 7 - Eigen Frequency and Displacement Profiles, Electric Potential and Von Mises Stress Plots for Complete MEMS Piezoelectric Cantilever Device

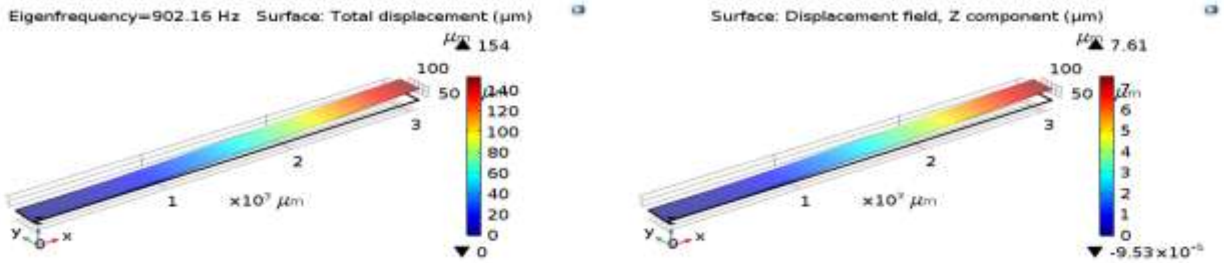
300 Hz

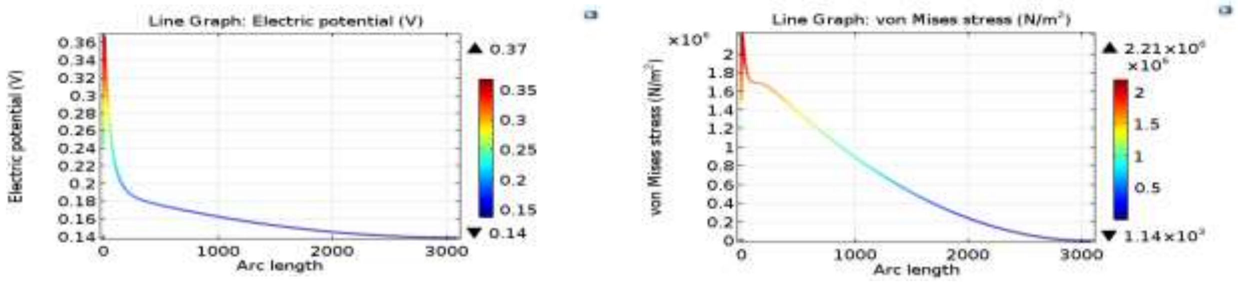


600 Hz

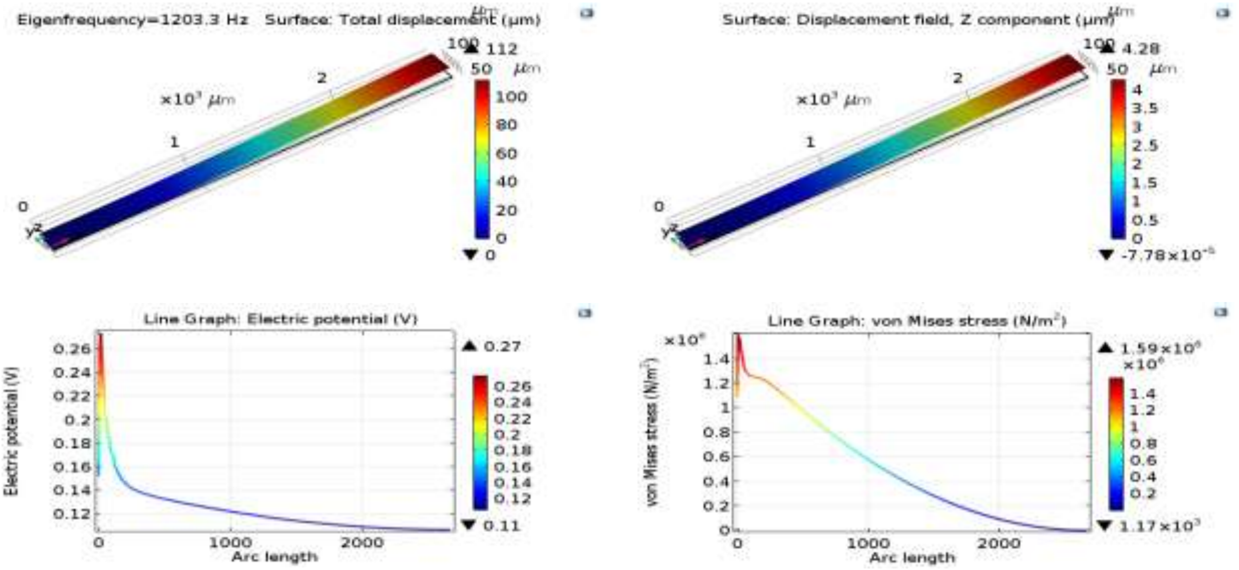


900 Hz

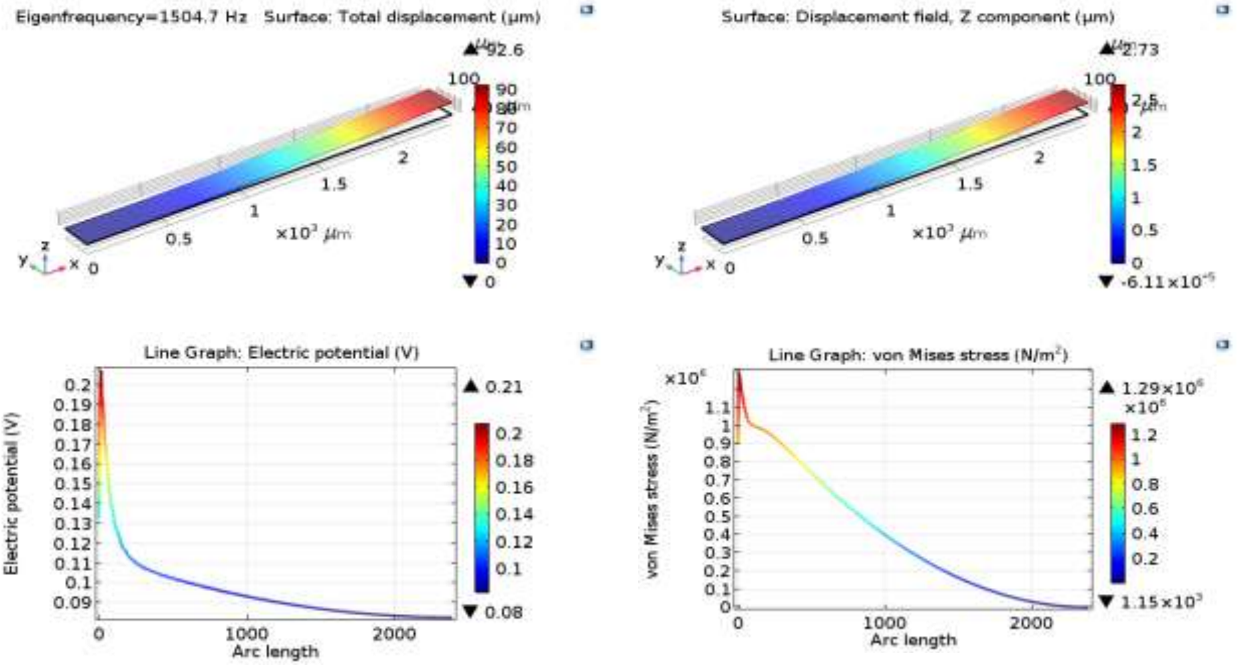




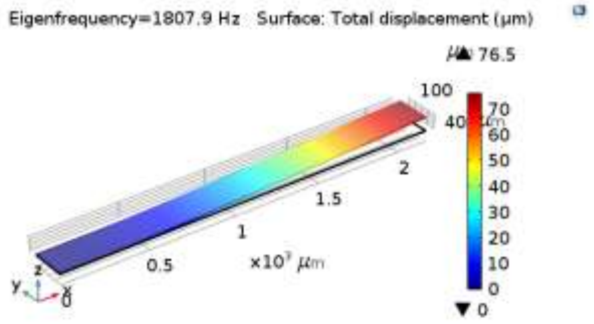
1200 Hz

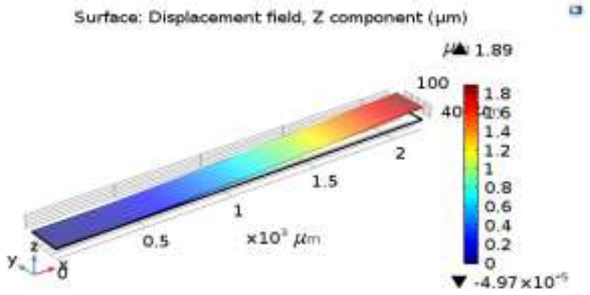


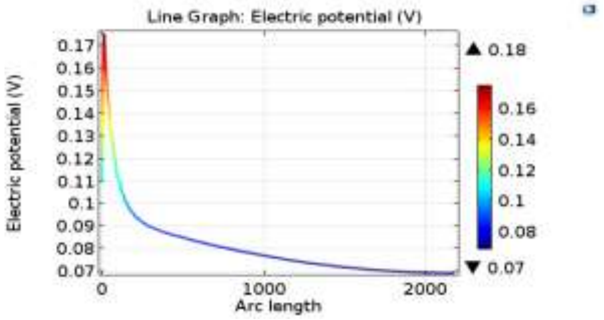
1500 Hz

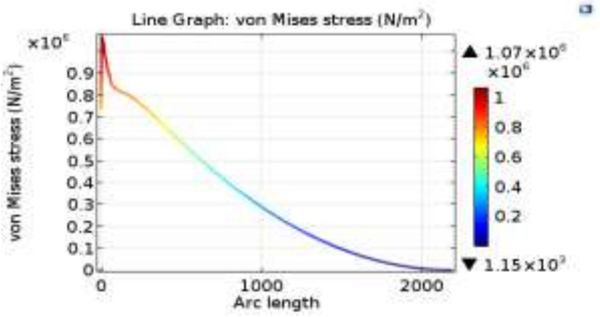


1800 Hz

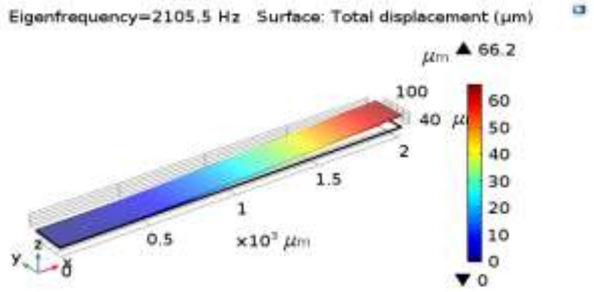


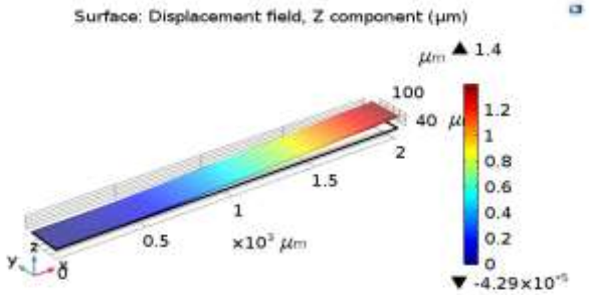


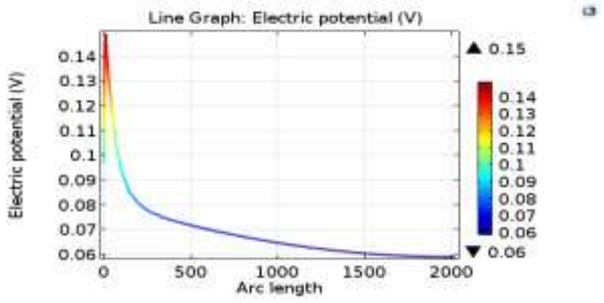


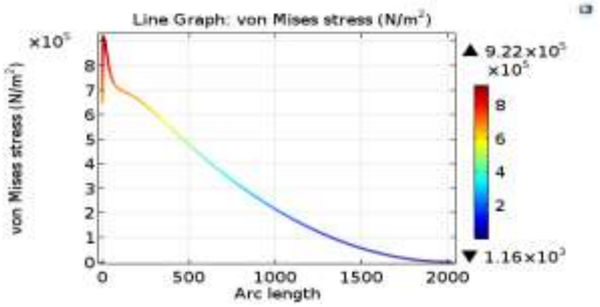


2100 Hz

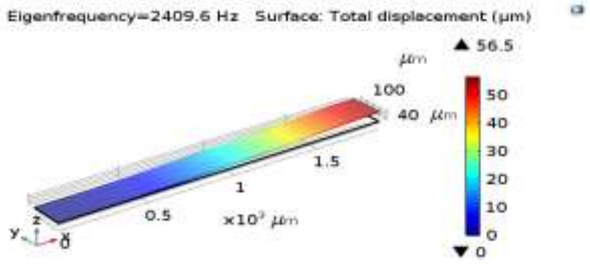


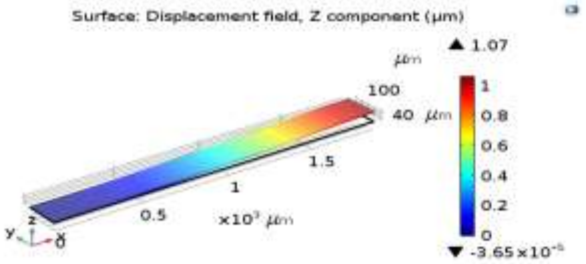


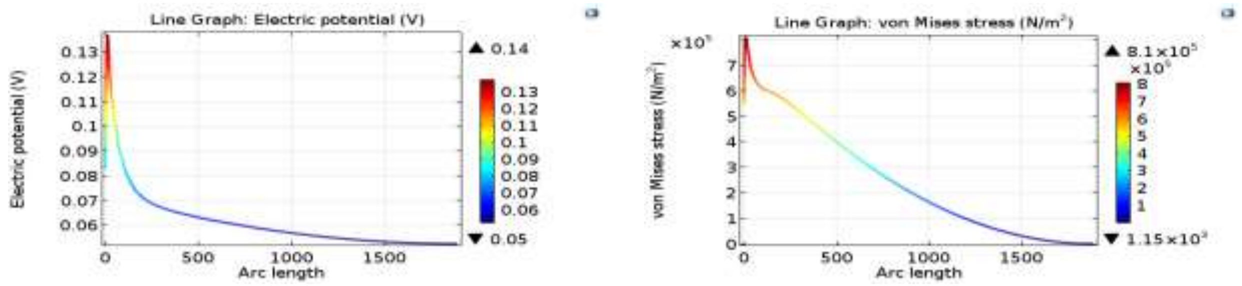




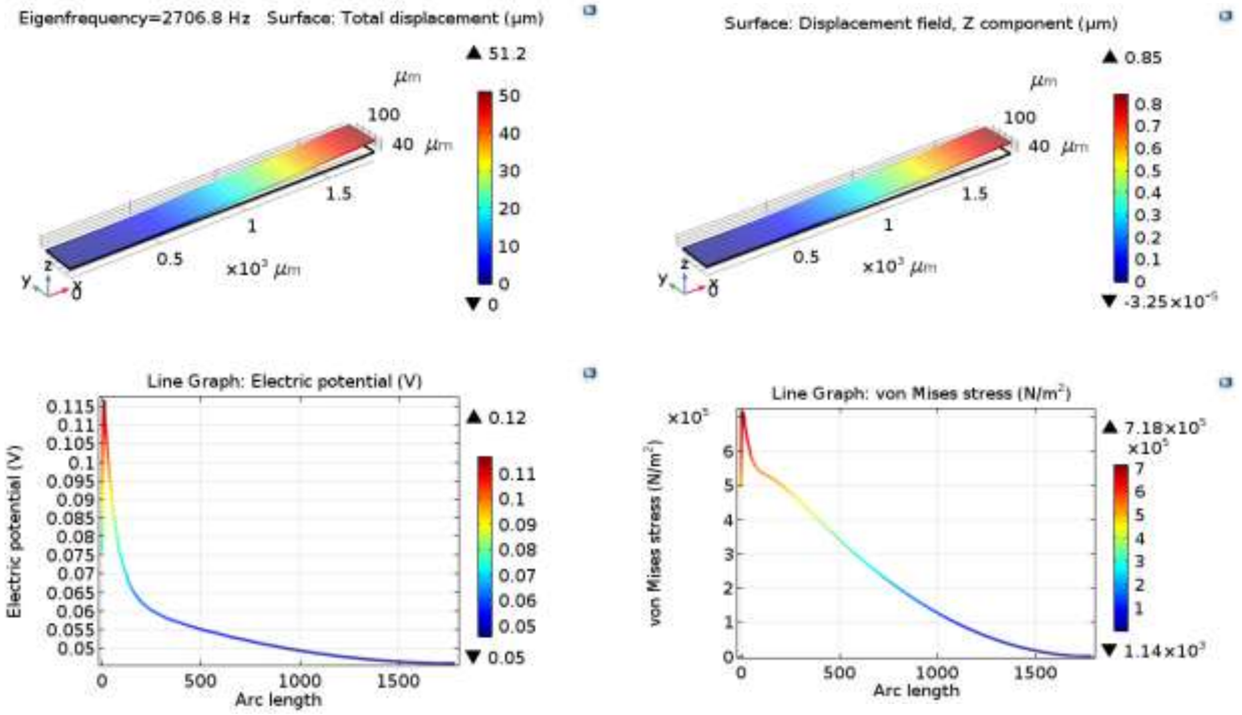
2400 Hz



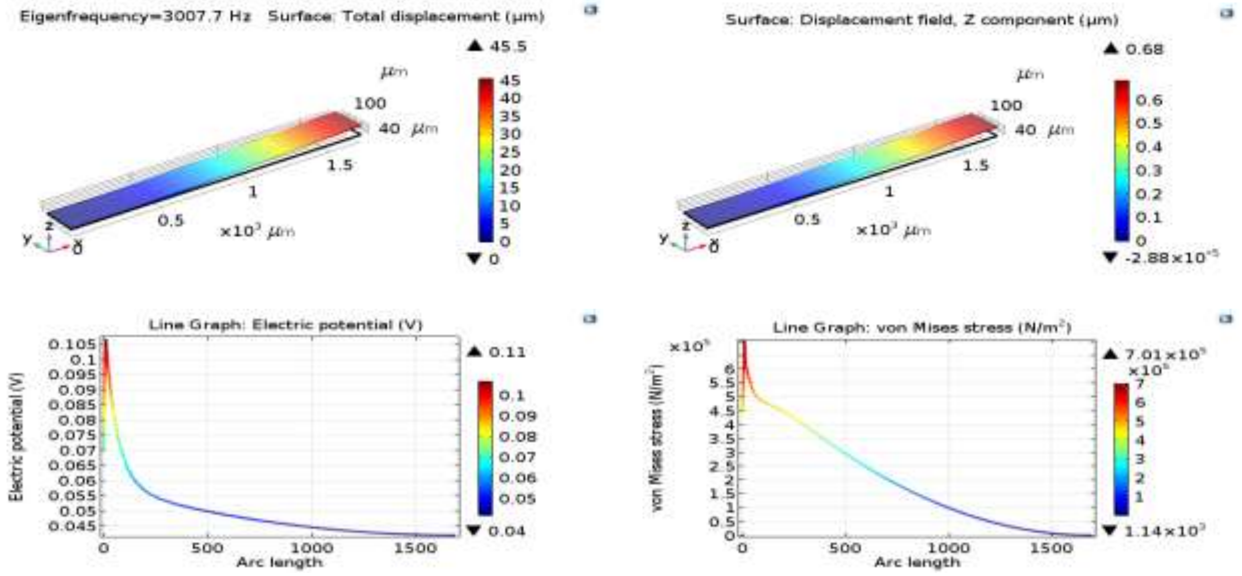




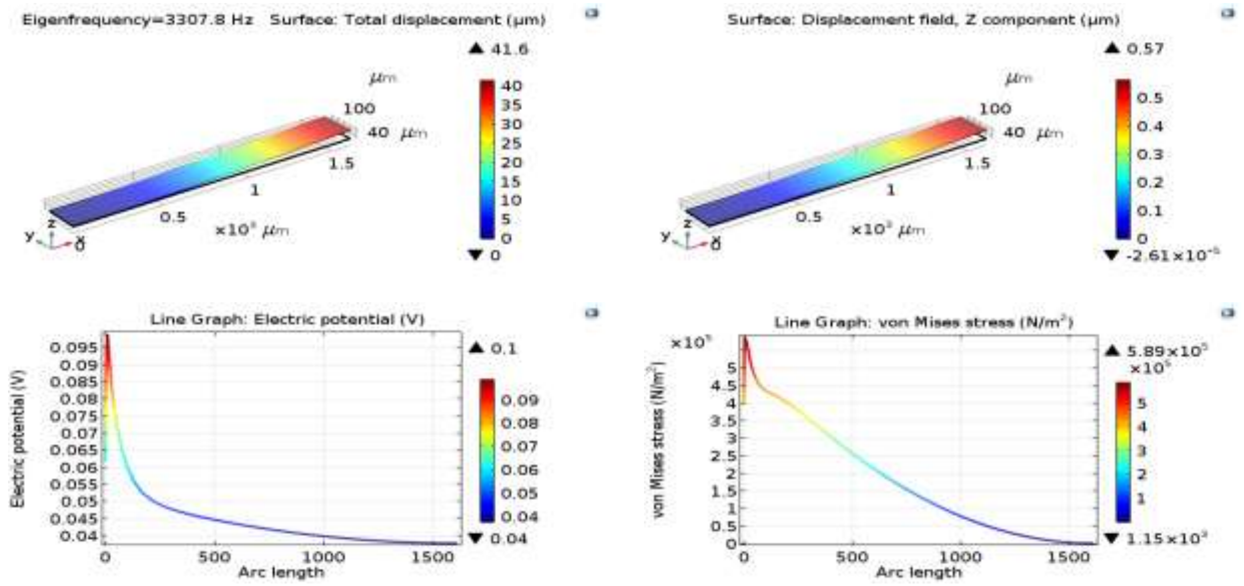
2700 Hz



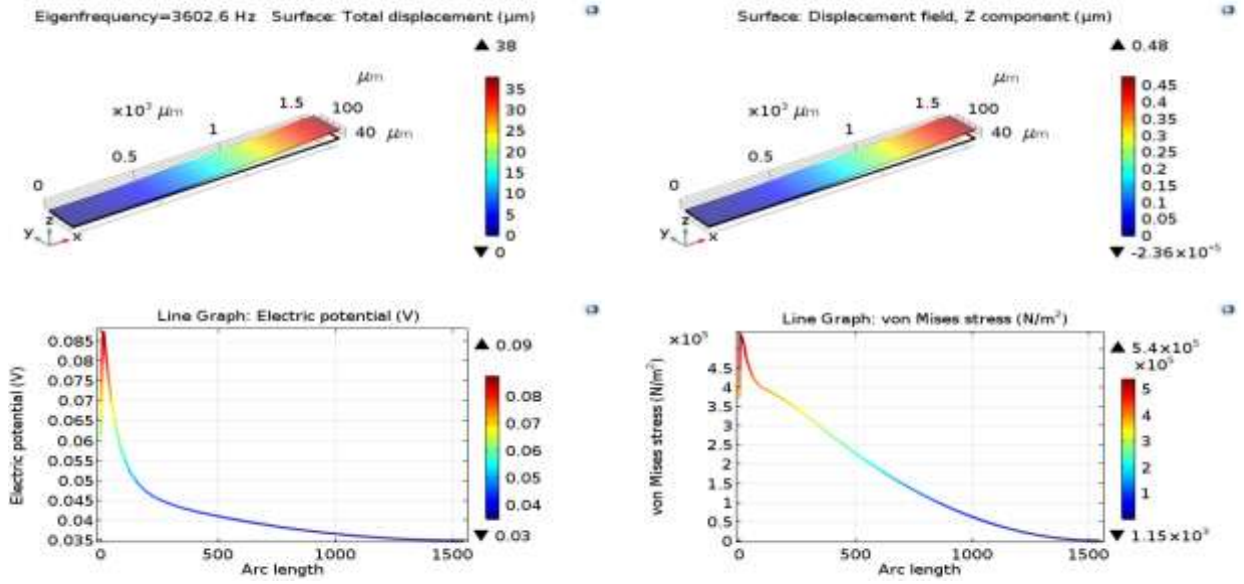
3000 Hz



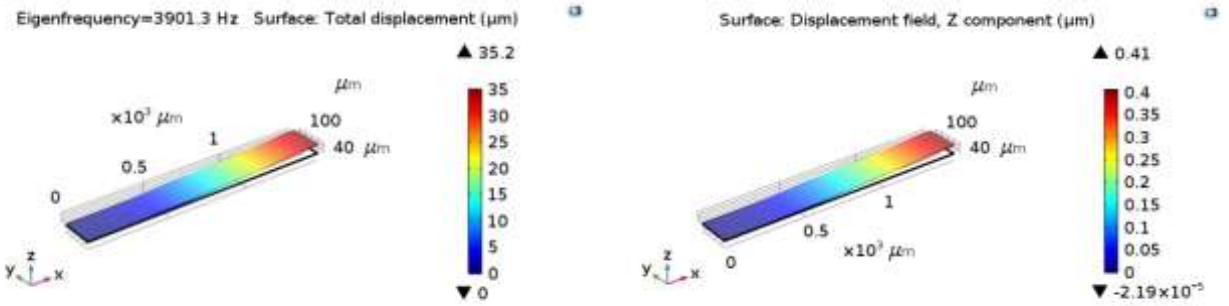
3300 Hz

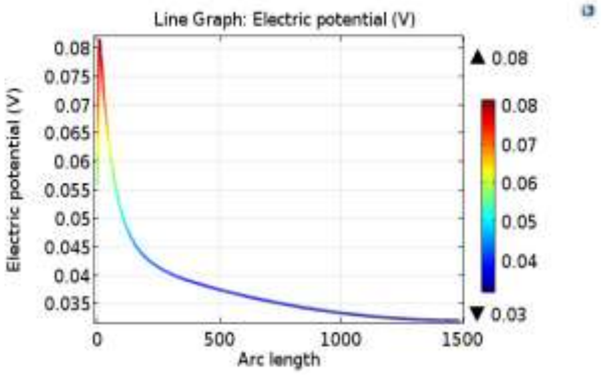


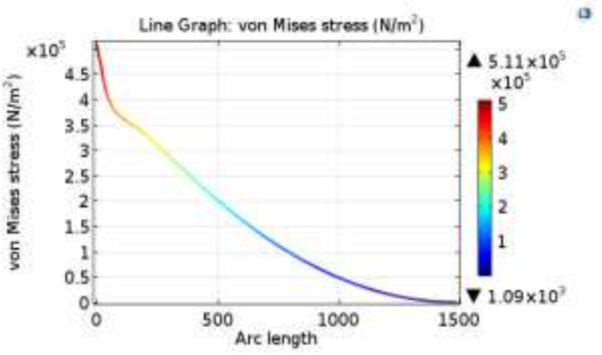
3600 Hz



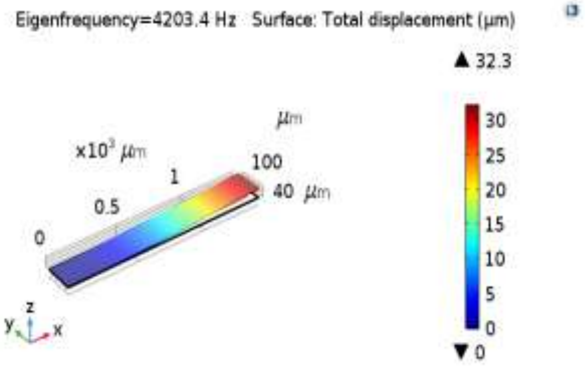
3900 Hz

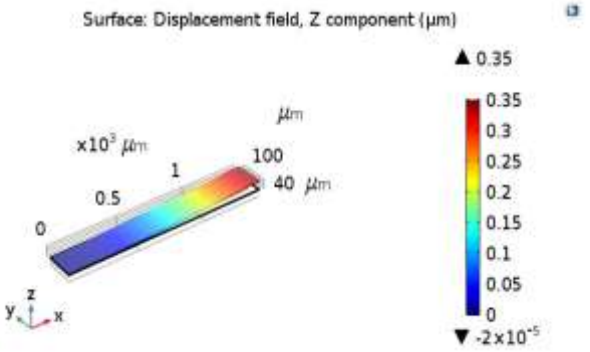


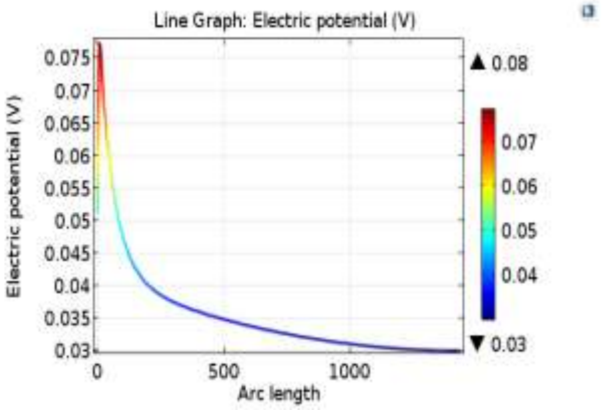


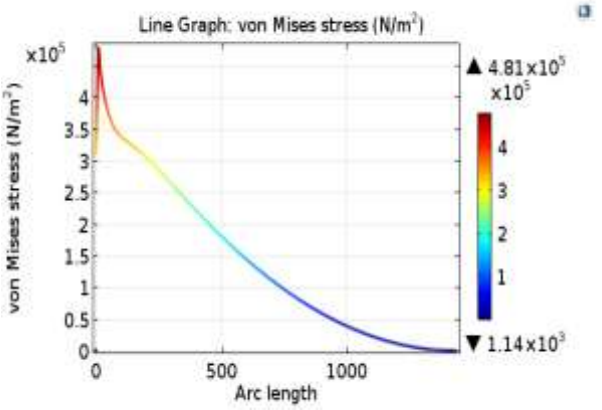


4200 Hz

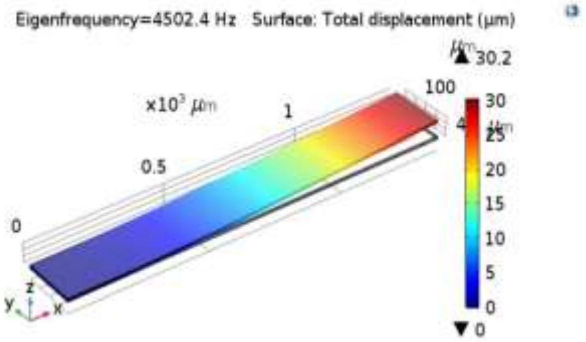


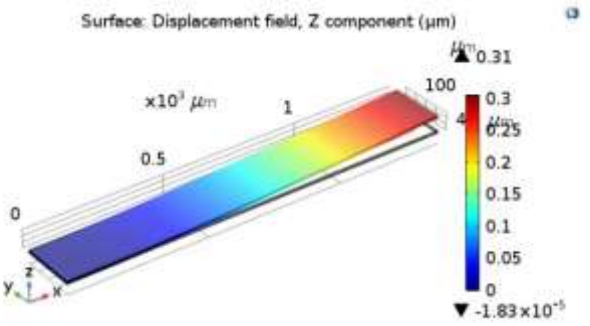


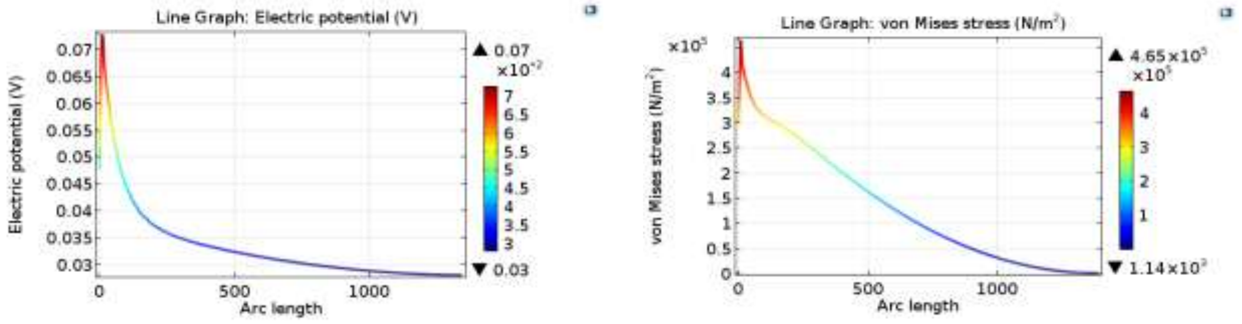




4500 Hz







4800 Hz

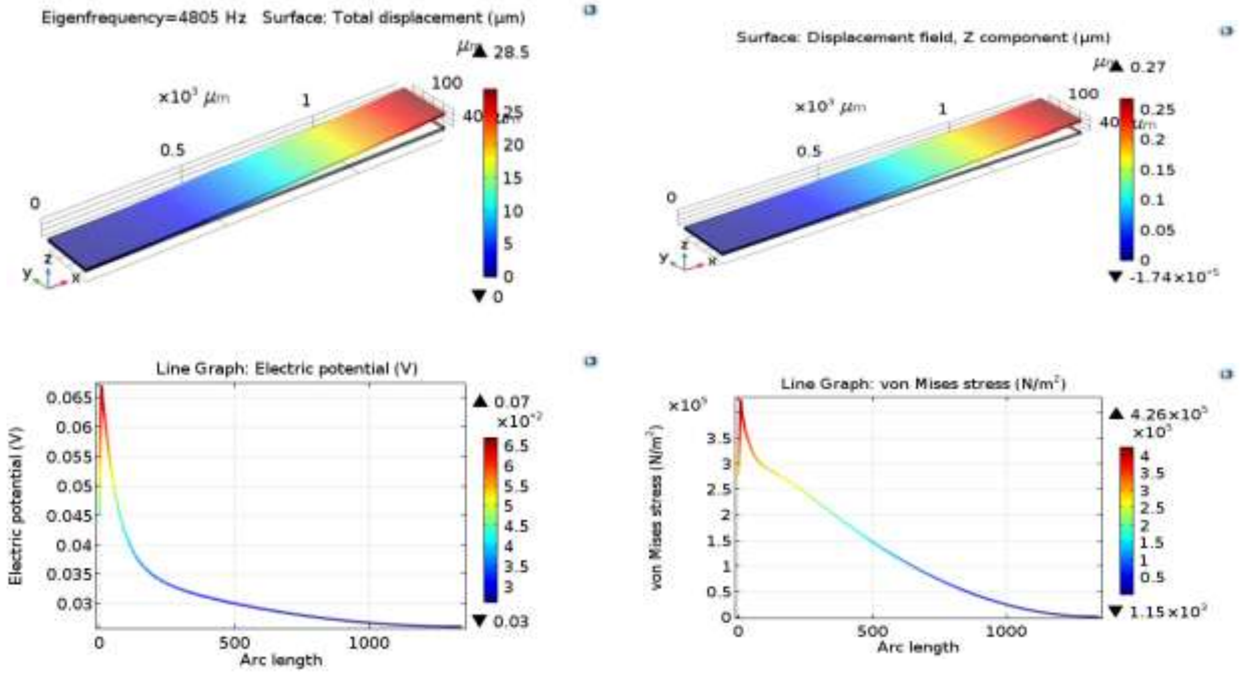
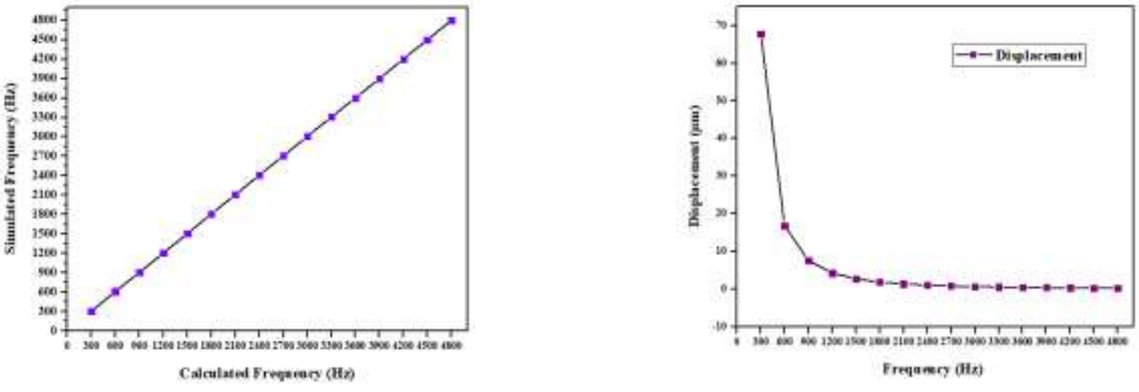


Figure 8 - a) Calculated Frequency Versus Simulated Frequency for MEMS Piezoelectric Cantilever Device

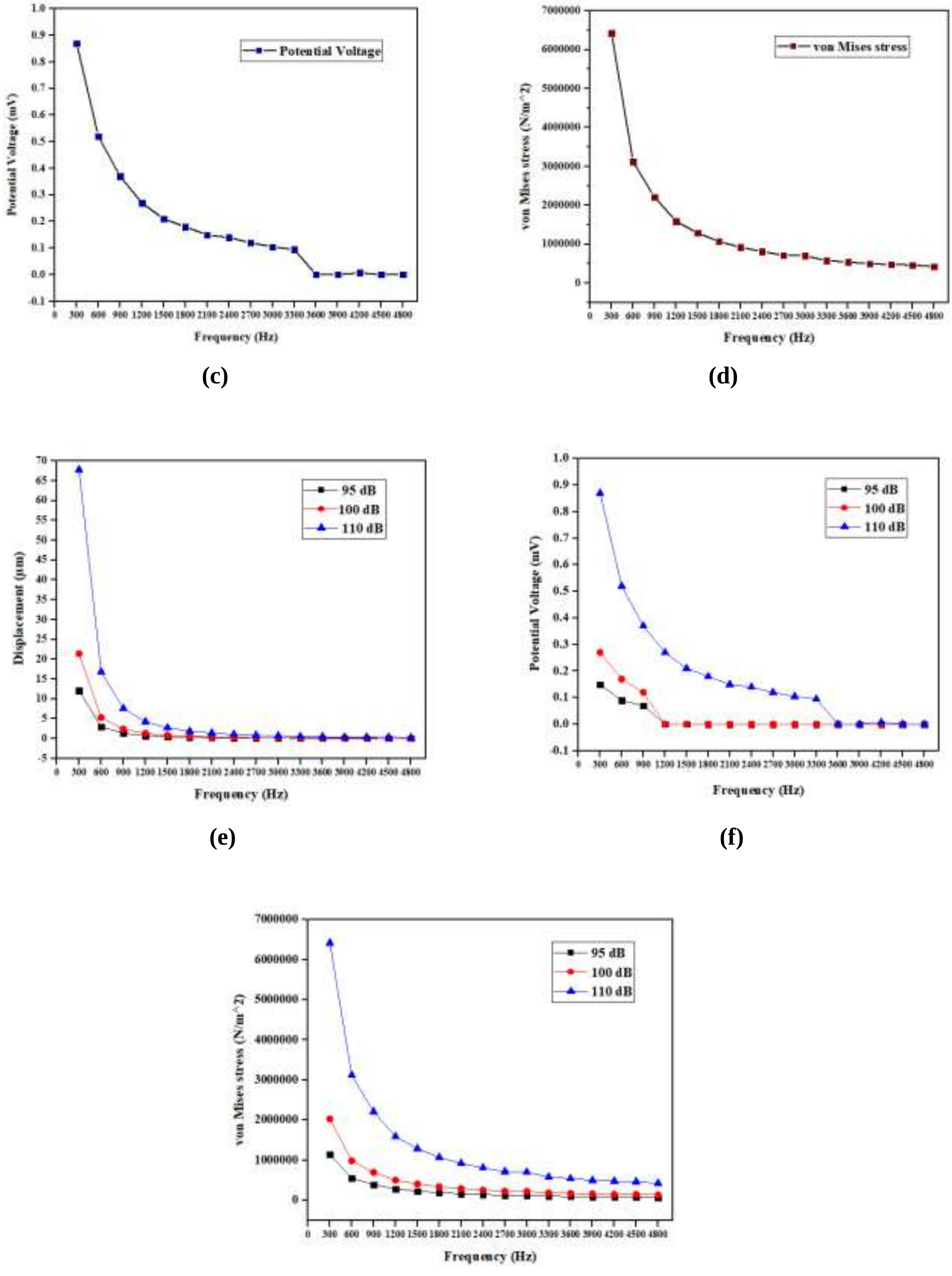
b), c), d) - Displacement, Electric Potential Voltage, Von Mises Stress Versus Frequency Plots Simulated by COMSOL Multiphysics

e), f), g) - Displacement, Electric Potential Voltage, Von Mises Stress Versus Frequency for Input Pressure Level of 95 dB, 100 dB and 110 dB



(a)

(b)


Potential Voltage (mV)
Potential Voltage
Frequency (Hz)
von Mises stress (N/m^2)
von Mises stress
Frequency (Hz)
Displacement (µm)
95 dB
100 dB
110 dB
Frequency (Hz)
Potential Voltage (mV)
95 dB
100 dB
110 dB
Frequency (Hz)
von Mises stress (N/m^2)
95 dB
100 dB
110 dB
Frequency (Hz)
0
300
600
900
1200
1500
1800
2100
2400
2700
3000
3300
3600
3900
4200
4500
4800

(c) (d)

(e) (f)

(g)

Fig 8 a shows a linear curve that matches the simulated frequency matches with the calculated frequency using equation 11. Figure 8 b illustrates that displacement is inversely proportional to the frequency for an input of 110 dB SPL. Simultaneously, electric potential voltage and Von Mises Stress vary with increase in frequency ranges from 300 to 4800 Hz and the corresponding curves are plotted in Figures 8 c and 8 d. Comparison of different input sound pressure levels for 95 dB,100 dB and 110 dB of displacement, Electric potential voltage, Von Mises stress versus frequency plots are shown in Figures 8 e, f and g. Hence, the change in input sound pressure level increases the output parameters.

5. Discussion

A number of technologies have been examined to implement the middle ear hearing device based on MEMS piezoelectric sensor. However, the traditional hearing device exhibit large dimension and consume more power. In the existing design, eight cantilevers were fabricated by Ilik et al. (2018) on thin-film piezoelectric transducer for a fully cochlear implantable sensor with two different audible frequency ranges from 300-4800 Hz and 250–5000 Hz with the input SPL of 100 dB and 110 dB is applied to generate the maximum voltage of 22.98 mV and 114 mV was obtained using Lase Doppler Vibrometer and the output voltage was measured using an oscilloscope [13,14]. Udvardi et al. (2017) propose a test array of sixteen cantilever beams on Spiral-Shaped Piezoelectric MEMS Cantilever was fabricated by bulk micromachining technique on a Si-on-Insulator (SOI) wafer and aluminum nitride (AlN). The main aim to cover the low frequency range of 300-700 Hz with an SPL of 110 dB. This experiment was conducted on a 3D printed sample which was mounted on a shaker table [15]. Yuksel et al. (2019) investigated with eight cantilever beams on a Multi-channel thin-film piezoelectric acoustic transducer was fabricated with PLD-PZT piezoelectric layers. The input SPL of 110 dB is applied at 316.4 Hz to generate the maximum output voltage of 139.36 mV by Finite Element Method modeling for cantilever resonance frequencies and shaker-table [16]. When compared to previous research group studies on MEMS piezoelectric acoustic transducers this device proposed Multi-channel MEMS piezoelectric cantilever device (PCD) for a fully cochlear implantable sensor with sixteen cantilever beams within the area of 4.3 x 2.4 mm more efficient. The main aim of this device is to generate a high electric potential voltage of 870 mV at 110 dB SPL over the resonance frequency range of 300-4800 Hz. The different input SPL was simulated and its output parameters are analysed using COMSOL Multiphysics.

6. Conclusion

MEMS piezoelectric cantilever device (PCD) for a fully cochlear implantable sensor is developed. The performance of the sensors is analysed when it is placed on the ear drum to stimulate the auditory nerve via cochlea and passes information to the brain. The implant system generates a high electric potential voltage of 870 mV for a frequency of 300 Hz at 110 dB SPL over a small sensing area of 4.3 x 2.4 mm which is more feasible and efficient by using piezoelectric cantilevers. This piezoelectric sensor is optimised such that it can be implanted surgically and works within the audible frequency range. The significant improvement of electric potential voltage, stress and displacement is validated by simulating on COMSOL Multiphysics and the results were discussed over previous works. The next step for future work, the more channels can be added if needed. The structure and dimension of the device can be improved, mathematically analysed and optimized to get maximum electric potential voltage for cochlear implant applications.

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