Simulation Study and Performance Optimization of Piezoelectric MEMS Device For Acoustic Sensor Applications

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Abstract—This paper presents simulation study and performance optimization of piezoelectric sensors to detect acoustic pressure inside the rail tracks. The structure of Piezoelectric MEMS Sensor is designed using COMSOL Multiphysics software which uses finite element method to compute the results. The structure is first simulated for five different piezoelectric materials i.e. Lead Zirconate Titanium (PZT-5H), PZT-5A, Zinc Oxide (ZnO), Quartz and Rochelle salt to optimize the output voltage. Further optimization is performed at the geometry level by varying the thickness of the piezoelectric sensor and at the input level by simulating the model for different pressures. A comparison between the performances of circular and rectangular piezoelectric sensor structures has also been reported.

Keywords—COMSOL, Rolling noise, PZT-5A, PZT-5H, ZnO, SAWS, Energy Harvesting.

I. INTRODUCTION

The piezoelectric materials are the active transducers that play a key role in sensor and actuator applications. In piezoelectric materials, an applied mechanical stress generates a voltage which is also known as direct effect. Conversely, an applied voltage will change the dimensions; this is the indirect effect. If a varying voltage is applied, the material will vibrate and the vibrations of appropriate frequency will produce the sound. Similarly, vibrations will produce small voltage. As the piezoelectric device generate voltage, it can be used as an energy harvesting device [1], and its thickness [2] can be optimized to generate more voltage. Pati et al [3] implement piezoelectric device as surface acoustic wave sensor (SAWS). In rail, vibrations are induced due to the rolling noise [4], [5]. Rolling noise arises due to the irregularity in rail and train wheel. These vibrations generated by train wheel travel in rails as an acoustic wave with a speed of 5960 m/s. These acoustic waves can be sensed by the piezoelectric sensor to generate small voltage.

Piezoelectric effects are strongly orientation dependent [6]. A piezoelectric material needs to be poled in a particular direction to provide a strong piezoelectric effect, although some materials exhibit natural or spontaneous polarization. The direction of positive polarization is customarily chosen to coincide with the Z-axis of a rectangular system of crystallographic axis X, Y, and Z. Fig.1 shows schematic illustration of piezoelectric crystal in rectangular system.

In a piezoelectric crystal, the constitutive equation [7], [8] that relates electrical polarization (D) and applied mechanical stress (T) can be written as:

\[ D = \varepsilon T + \sigma E \]  \hspace{1cm} (1)

Where \( d \) is the piezoelectric coefficient matrix (3x6), \( T \) is stress, \( E \) is the electrical permittivity matrix (3x3) and \( E \) is the electric field. Similarly, the expression for inverse effect of piezoelectricity can be written as:

\[ s = S T + \sigma E \]  \hspace{1cm} (2)

Where \( s \) is the strain produced, and \( S \) is the compliance matrix (6x6). The piezoelectric effect occurs only in non conductive materials. Piezoelectric materials can be divided in two main groups: crystals and ceramics. Crystals can be classified into 32 groups according to crystal symmetry. Centro symmetric crystal structures are crystals that are symmetric along all the axis through the centre of the crystal. These crystals occupy 11 out of 32 possible groups and are non-piezoelectric material because, positive and negative charge sites will not be spatially separated under stress. Out of 21 non-centro symmetric groups, 20 are piezoelectric crystals. Table-I shows the properties [9], [10], [11], [12] of different piezoelectric materials used for the simulation of piezoelectric MEMS sensor.
Table 1 Properties of the piezoelectric materials used during simulation

<table>
<thead>
<tr>
<th>S.No</th>
<th>Materials</th>
<th>Young’s Modulus (GPa)</th>
<th>Poisson’s Ratio</th>
<th>Density (Kg/m³)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Quartz</td>
<td>95.6</td>
<td>0.084</td>
<td>2650</td>
</tr>
<tr>
<td>2</td>
<td>ZnO</td>
<td>112</td>
<td>0.336</td>
<td>5600</td>
</tr>
<tr>
<td>3</td>
<td>PZT-5H</td>
<td>64</td>
<td>0.33</td>
<td>7500</td>
</tr>
<tr>
<td>4</td>
<td>PZT-5A</td>
<td>66</td>
<td>0.33</td>
<td>7750</td>
</tr>
<tr>
<td>5</td>
<td>Rochelle Salt</td>
<td>19.1</td>
<td>0.196</td>
<td>1767</td>
</tr>
</tbody>
</table>

II. MOUNTING OF THE SENSOR

Fig. 2 shows a railway rail which is resting on the concrete sleeper. The piezoelectric sensor assembly is mounted on the side of the rail as shown in the figure. The rail is attached to the piezoelectric sensor and the backing substrate is attached to it in order to provide mechanical support to the sensor. The piezoelectric sensor is divided into four quarters. The voltage is taken across the quarter 1 and its opposite by keeping the both at ground and floating potential respectively. The quarter 2 and the one opposite to it are at fixed potential. The assembly of the sensor and the backing substrate is mounted in such way that maximum vibrations can be obtained at the output.

Fig. 3: Schematic of COMSOL simulated circular and rectangular sensors.

III. SIMULATION OF PIEZOELECTRIC SENSOR

The simulation of piezoelectric sensor is done using COMSOL Multiphysics software [13]. The complete geometry is shown in Fig. 3. It consists of rail which is made of steel, a sensor which is made of piezoelectric material and a backing substrate which is made of nylon. The backing substrate protects the sensor from the environmental effects and it reduces the backward vibrations.

The complete structure has four domains. Free tetrahedral mesh is used for meshing all domains. Three physics interfaces, Solid Mechanics, Piezoelectric Device and Acoustic Solid Interaction have been used during the simulation. When pressure was applied on the rail; the generated stress resulted in the displacement of the piezoelectric device. As the piezoelectric displacement takes place, a small voltage is produced. This small voltage indicates that the vibrations has taken place in the rail. The von mises stress and the total piezoelectric displacement at time instant of \( t = 0.03 \) sec are shown in Fig. 4(a) and Fig. 4 (b) respectively.

![Von Mises Stress at t=0.03s](image)

![Total Displacement in Circular Sensor at t=0.03s](image)

The values of minimum and maximum stress obtained from Fig. 4(a) are 0.4631 N/m² and 1.599×10⁶ N/m² respectively. Fig. 4(b) shows that the minimum displacement is 0 cm and the maximum displacement is 8.1669×10⁻⁴ cm for the simulated circular sensor. Similarly, the Rectangular Piezoelectric device is simulated in COMSOL Multiphysics and, von mises stress and total displacement is shown in Fig. 5(a) and Fig. 5(b) respectively.

![Von mises stress at t=0.025s](image)

![Total displacement in rectangular sensor at t=0.025s](image)

Figure 5(a) shows that the minimum stress is 7.7335 N/m² and the maximum stress is 3.0017×10⁶ N/m² for the simulated structure. Fig. 5(b) shows that the minimum displacement is 0 cm and the maximum displacement is 0.194 cm for the simulated rectangular structure.
IV. GLOBAL EVALUATION

A. Material Optimization:
Fig. 6 compares the performance of different piezoelectric materials (such as PZT-5H, PZT-5A, Zinc Oxide (ZnO), Quartz, and Rochelle salt) for circular piezoelectric sensor. It has been observed that PZT-5H gives the minimum output voltage while the Rochelle gives the maximum output for the simulated structure. The material properties have been taken according to the Table 1.

![Fig. 6: Performance comparison of different piezoelectric materials (PZT-5H, PZT-5A, Zinc Oxide (ZnO), Quartz, and Rochelle salt) for circular piezoelectric sensors.]

B. Thickness Optimization:
Fig. 7 and 8 shows the effect of piezoelectric material thickness on the performance of circular and rectangular piezoelectric sensors. The different values of thicknesses were taken as 0.03cm, 0.04 cm, 0.06 cm, 0.07 cm respectively during the simulation. It is clear from Fig. 7 that the minimum output voltage is obtained at 0.07 cm thickness and the maximum output voltage is obtained at 0.03 cm thickness for circular piezoelectric sensor. As the sensor thickness increases the output voltage decrease because total piezoelectric displacement decreases with increased thickness. Similarly the minimum and maximum output voltage for rectangular piezoelectric sensors was obtained at 0.07cm and 0.04cm thickness respectively.

![Fig. 7: Thickness optimization of circular piezoelectric sensor.]

![Fig. 8: Thickness optimization of rectangular piezoelectric sensor.]

C. Geometry Optimization:
The optimized thickness found for circular sensor is 0.06cm and for rectangular sensor the optimized thickness is 0.04cm. Fig. 9 shows the geometry optimization of circular and rectangular piezoelectric sensors. It is clear from the figure that circular sensor gives the better output voltage than the rectangular sensors.

![Fig. 9: Geometry Optimization of circular and rectangular piezoelectric sensors.]

D. Frequency Optimization:
Fig. 10 shows the frequency optimization of circular piezoelectric sensor in the frequency range of 50Hz to 500 Hz. It has been observed that the output voltage has first increased for a frequency range of 50Hz to 450Hz and then from 450Hz onwards it has decreased sharply. After 450Hz the device polarized and depolarized rapidly, therefore the voltage start decreasing.

![Fig. 10: Frequency optimization of circular piezoelectric sensor.]

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CONCLUSION

This work reports the simulation study and performance optimization of circular and rectangular piezoelectric acoustic sensors. Results confirmed that both the sensors have detected the acoustic signals successfully. It has been observed that the performance of circular sensor is better than the rectangular one. It is seen that the output voltage has decreased with the increasing thickness of different piezoelectric materials in both the sensors. Rectangular sensor design was found to be less sensitive to the noise than the circular design. The output voltage was found to be minimum for PZT-5H, and maximum for Rochelle salt. The sensors have demonstrated a good performance in the frequency range 50 Hz to 450 Hz, but after 450 Hz, sensor output voltage has started to reduce. Results conclude that these kind of sensors can be used for energy harvesting applications. This energy can also be used as source for low power circuit applications.

REFERENCES