



COMSOL Multiphysics Simulation of Piezoelectric Sensor for Energy Harvesting from Railway tracks

Anuj Jain, Surender Kumar, Ashutosh Kharb

Abstract: An energy harvester using piezoelectric sensors is investigated and a model is simulated in COMSOL multiphysics software to harness energy from railway tracks. In new energy conservative world, new ideas are needed to be implemented. The induced sound wave inside the railway tracks, as a result of rail wheel interaction, is of dynamic in nature. These waves are travelling in the railway tracks for short time of interval and can be easily harvested with the help of piezoelectric sensors and stored inside the batteries for later use. Now a day's wireless sensor nodes are widely used for measurement of different physical quantities like temperature, humidity etc. and providing essential power to such devices, is a big problem. Energy harvesting from tracks can be used to power wireless sensor nodes installed near to railway tracks, tunnels, and rural areas near railway tracks. The Lead Zirconate Titanate PZT 5H piezoelectric sensors are used to simulate a model in COMSOL.

Keywords : COMSOL Multiphysics, Lead Zirconate Titanates (PZT), Energy harvesting, Rolling Noise, Piezoelectric sensor, Electrical Circuit

I. INTRODUCTION

Energy harvesting now a days is very popular field among the researchers especially using piezoelectric elements. These materials are mainly important for their use as actuator (converse effect) and as sensors (direct effect). Piezoelectric sheets have been used by many researchers as sensors in the area of structures with controllability systems and other applications like health monitoring [1,2]. A more important area of Piezoelectric sensors is energy harvesting devices [3]. Lead Zirconate Titanates (PZT 5H) is the sensor used by authors in order to investigate the induced waves inside the rails of railway tracks. The measurement technique is presented in [4]. In this paper authors have shown that these acoustic waves can be used to harvest energy. Two or more number of similar piezoelectric sensors may be used to have more power. This harvested energy is useful for wireless

sensor nodes acting near to railway tracks, tunnels, rural areas and other places where delivering power is a big issue.

An effective model is proposed by John J. Wang et. al. [5] to harness the vibrational power from the railway track deflections. An electromagnetic energy harvester is used to harness these deflections due to the passing trains for higher power applications for major trackside instruments and equipments such as switches, warning lights and sensors for health monitoring, typically required power of 10 watts or more. They used motion conversion mechanism to converts bidirectional irregular pulse-like linear vibration into regulated unidirectional rotational motion. An efficient electromagnetic energy harvester featured with mechanical motion rectifier (MMR) is proposed by Teng lin et. al. [6] to recover energy, from vibration like railroad track deflections induced by passing trains.

Now a day, many software are available to investigate numerical problems. COMSOL Multiphysics FEM software is one of such software for the numerical solution based on different simulation environment. I. Bueth and C.P. Frizen [7] designed Active Sensors based on piezowafers in COMSOL software and studied it's behavior in frequency as well as in time domain and validated the results by comparing to experimental results. M. Guizzetti et al [8] simulated a proposed model of piezoelectric energy converter. It has a shape of a cantilever and converted the mechanical vibration into electric energy. To understand the effect of adhesive layer on the electromechanical coupling of piezoelectric sensors bounded to structure, a COMSOL model was carried out by H.A. Tinoco et al [2] and proved that the adhesive layer has significant effect on the mechanical as well as electrical behavior of structure and PZT sensor. A very good description about the use of COMSOL Multiphysics is presented by Rakesh Kumar Pati et al [9], regarding the design steps of AIN based pressure sensor.

II. ACOUSTIC WAVE INSIDE RAILWAY TRACK

Rolling noise is mainly produced due to the interaction of train wheels with the rail tracks and it vibrates inside the rail tracks as well as in air. The induced vibration inside tracks are capable to travel in forward direction as well as in reverse direction. Hence piezoelectric sensors are the perfect devices to harvest energy from these waves. Fig. 1 is used to show the generation mechanism of rolling noise [10, 4]. It is clearly evident here that wheel rail interaction is inducing vibration in railway tracks as well in air and is directly related to speed. It is directly proportional to the speed of train and is more effective at a speed of 50 Km/h and above.

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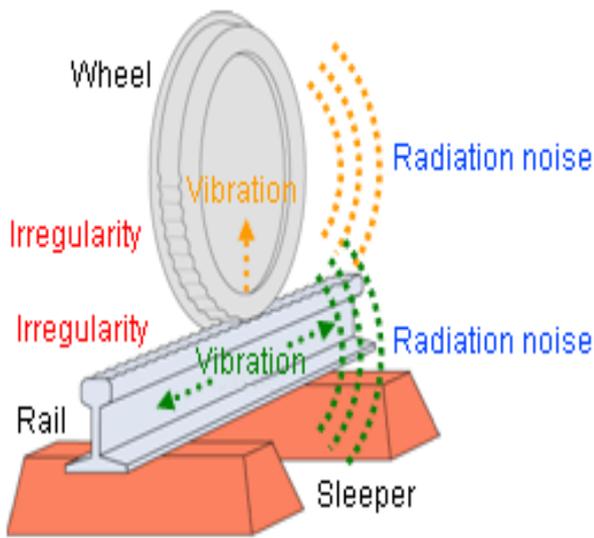


Fig. 1 Generation of Rolling Noise [4,10]

III. PIEZOELECTRIC CONSTITUTIVE RELATIONS

Followings are the constitutive relationship under small field conditions for a piezoelectric material. [11, 16]

$$D_i = e_{ij}^{\sigma} E_j + d_{im}^d \sigma_m \quad (1)$$

$$\varepsilon_k = d_{jk}^c E_j + s_{km}^E \sigma_m \quad (2)$$

Rewritten in matrix form as

$$\begin{bmatrix} D \\ \varepsilon \end{bmatrix} = \begin{bmatrix} e^{\sigma} & d^d \\ d^c & s^E \end{bmatrix} \begin{bmatrix} E \\ \sigma \end{bmatrix} \quad (3)$$

Description of parameters used in above equations are shown in Table 1.

Table 1: Description of parameters used in above equations

Vector	Matrix size	Description	Unit
D	3*1	Electric displacement	Coulomb/m ²
ε	6*1	strain vector	dimensionless
E	3*1	applied electric field vector	Volt/m
σ_m	6*1	stress vector	N/m ²
e_{ij}^{σ}	3*3	dielectric permittivity	Farad/m
d_{im}^d	3*6	piezoelectric coefficients	Coulomb/N
d_{jk}^c	6*3	piezoelectric coefficients	m/Volt
s_{km}^E	6*6	electric compliance	m ² /N

Two piezoelectric constants d_{im}^d (Coulomb/N) and d_{jk}^c (m/Volt) defines electric displacement per unit stress at constant electric field and strain per unit field at constant stress respectively. The superscripts c and d have been added to differentiate between converse and direct piezoelectric effects, though in practice, these coefficients are numerically equal. A good explanation about piezoelectric sensors is presented in [1].

A. PZT Sensors

Piezoceramics, Lead Zirconate Titanates (PZT) are the most commonly used type and are solid solution of lead zirconate and lead titanate. These are often doped with certain other elements to obtain specific properties. Proportional amount of lead, zirconium and titanium oxide powders are mixed together and then heated all together at a temperature from 800 to 1000° C. The resultant is perovskite PZT powder. Then this powder is mixed with a binding solution and desired shapes are produced.

B. Electrical Response of the PZT Sensor

First Maxwell's equation can be used to determine the electrical signatures [1] produced by the piezoelectric sensor as a result of mechanical deformation. According to this, electric charge density q is related to electric displacement D_i as

$$q = \text{div}(D_i) \quad (4)$$

Hence the total electric charge accumulated inside the piezoelectric sensor is expressed as

$$Q = \iiint_V q \, dv \quad (5)$$

Volume of the piezoelectric sensor is V . The piezoelectric sensor, which behaves like a capacitor, due to its electrical charge and discharge effects produces voltage at electrodes and this can be obtained as

$$V_{pzt} = \frac{Q}{C_{pzt}} \quad (6)$$

Where C_{pzt} is the capacitance of the piezoelectric material (PZT) and it is calculated by

$$C_{pzt} = \frac{e_{33} A_p}{h_p} \quad (7)$$

Where e_{33} is the electric permittivity, A_p is the area of the PZT sensor and h_p is the thickness of sensor.

C. Mechanical analysis

The generic model developed by Williams and Yates [12, 15] is shown in Fig. 2 and the second order dynamic system relates the input vibrations $y(t)$ to the output displacement $z(t)$.

The dynamic equation according to D'Alembert's law is given as:

$$m \frac{d^2 z}{dt^2} + b \frac{dz}{dt} + kz = -m \frac{d^2 y}{dt^2} \quad (8)$$

Where k is spring constant, b is damping coefficient and m is mass.

As a result of damping on the system, mechanical power is transferred into electrical power due to the damper.

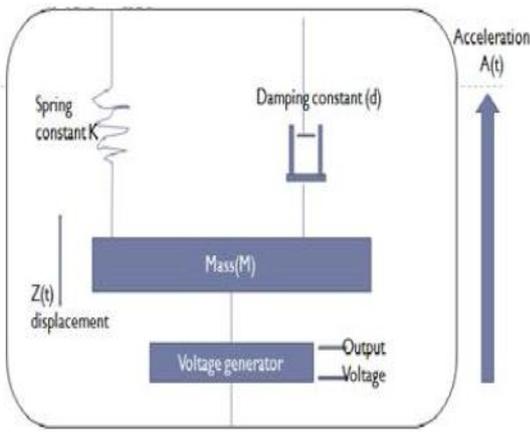


Fig 2. Generic model of PVEH [12, 15]

The applicable excitation is sinusoidal as

$$y(t) = Y \sin \omega t \tag{9}$$

The power generated is expressed as

$$p(\omega) = \frac{m \zeta_T Y^2 \left(\frac{\omega}{\omega_r}\right)^3 \omega^3}{\left(1 - \left(\frac{\omega}{\omega_r}\right)^2\right)^2 + \left(2 \zeta_T \frac{\omega}{\omega_r}\right)^2} \tag{10}$$

At resonant frequency, the harvested power from this model is maximum at resonant frequency and is expressed as

$$p = \frac{m a^2}{8 \omega_r} \cdot Q = \frac{F \cdot a}{8 \omega_r} \cdot Q \tag{11}$$

Where $a = Y \omega^2$, is the applied acceleration and Q is the quality factor of the piezoelectric material. It is clearly visible from (11) that the harvested power is directly proportional to the quality factor and applied force on the model. It is also evident that resonant frequency is inversely proportional to the harvested power. Therefore for higher energy production, low resonant frequency of the cantilever is preferable.

D. Electrical Equivalent circuit of PVEH

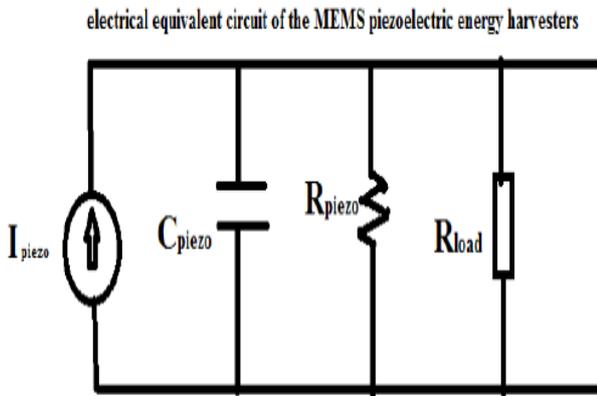


Fig 3. Electrical equivalent circuit of PVEH [12, 15]

The respective force equilibrium dynamic model can be transformed into the electrical circuit by using the force-voltage analogy shown in Fig. 3.

The harvester now can be represented as follows

$$- m a(s) = s \cdot Z(s) \left(m s + b + \frac{k}{s} \right) \tag{12}$$

It can be written as by employing the duality nature as follows

$$-I(s) = E(s) \left(sC + \frac{1}{R} + \frac{1}{sL} \right) \tag{13}$$

Where $I(s) = m a(s)$, $E(s) = s Z(s)$, $C = m$, $b = \frac{1}{R}$, $L = \frac{1}{k}$

At resonance the current source is equal to $I_{piezo} = m A \omega^2 n$ and since the harvester effective impedance is of capacitive type, so the input impedance is shown as

$$Z_i = \frac{1}{\omega_n C_{piezo}} \tag{14}$$

Therefore the maximum power is harvested, when the load impedance will be equal to the internal impedance Z_i .i.e., as per the power transfer theorem,

$$Z_{load} = Z_{input} \tag{15}$$

To store the electrical energy in a capacitor, it is given as

$$W(t) = \frac{1}{2} C V(t)^2 \tag{16}$$

Where $W(t)$ is the stored energy at instant of time t , and voltage V is the measured voltage across the capacitor. Since the charge density is accumulated on the surface of the piezoelectric layer and voltage is generated across it due to its capacitive effect. The total theoretical energy generated by the harvester can be modeled as

$$E = \frac{1}{2} QV \tag{17}$$

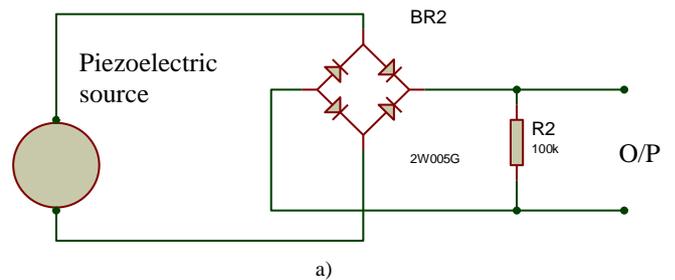
Where E –the energy generated, Q - the charge density of piezoelectric layer and the V is the voltage generated.

$$Q = \rho AT \tag{18}$$

Where A is the area of the charge accumulated and T is the thickness of the layer and ρ is the charge density of piezoelectric layer.

IV. COMSOL MODELLING

The modeling and simulation of piezoelectric sensor on rail beam is performed with the help of COMSOL Multiphysics software. This software can be used for modeling and solving various engineering problems. Being powerful integrated software, it can be used to build a model in model builder and simulate it with different physics [12]. Two physics, piezoelectric devices and semiconductor devices are used to analyze the model. The piezoelectric physics solves the problems based on the governing equations of piezoelectricity whereas semiconductor devices are used to simulate electric circuit equivalent of as shown in Fig.4.



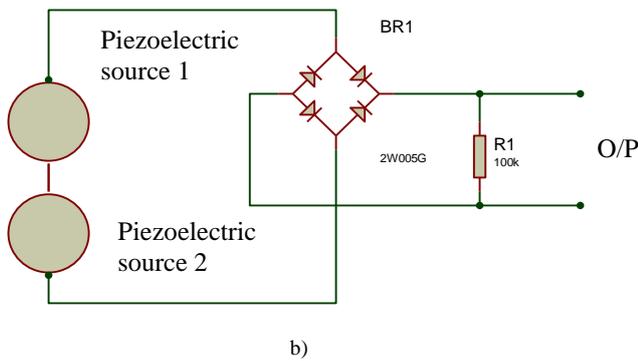


Fig. 4. Piezoelectric sensor as voltage source a) single crystal b) double crystal

A 3D geometry is considered for the simulation. Two piezoelectric sensors are modeled and placed on the rail beam as shown in Fig.5. Another model, for simplicity, is created by only assuming the piezoelectric devices as shown in Fig.6. Both the piezoelectric sensors are excited by the acoustic pressure applied through rail beam. Although the piezoelectric devices are placed at nearby locations on railway tracks, the pressure applied on each device is slightly different. It is assumed in this simulation that the pressure applied on all the piezoelectric devices is equal. The material for sensor is Lead Zirconate Titanate (PZT-5H). Fig.7 shows the 3D meshed geometry. Material properties of structural steel and PZT-5H are given in table 2.

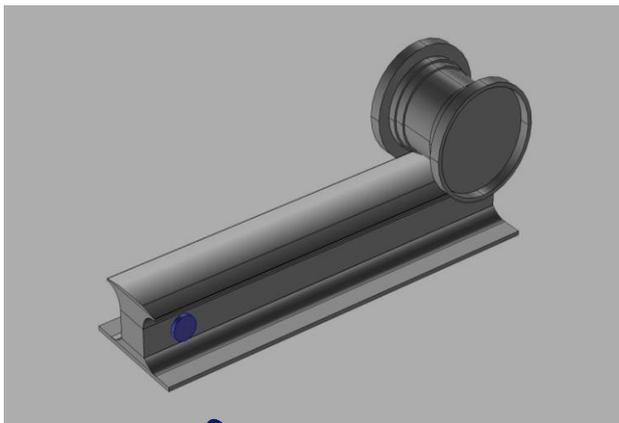


Fig. 5. Rail beam and Location of sensor

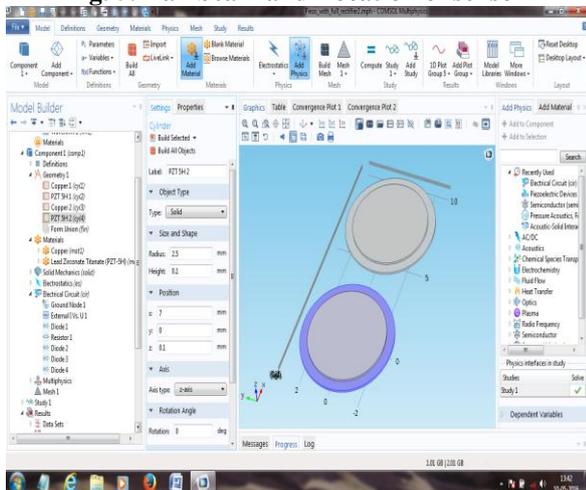


Fig. 6. Designing in COMSOL Multiphysics

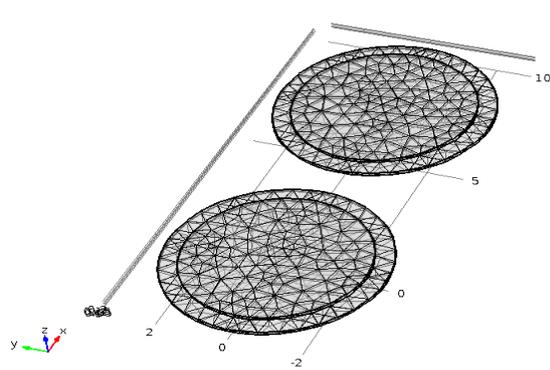


Fig. 7. Mesh of complete model

An incident acoustic pressure (p_{w1}) of 300000 Pa is used to excite the piezoelectric sensors by a plane wave radiation. The ground and floating potential terminals of sensor are shown in Fig. 8 and Fig. 9 respectively.

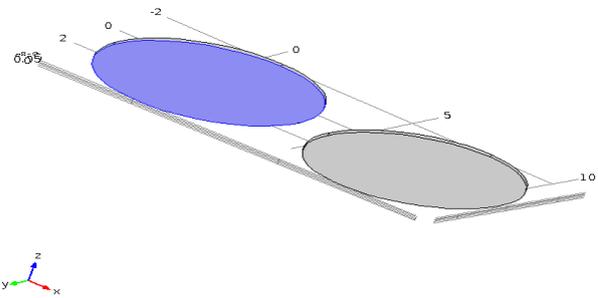


Fig. 8. Ground Terminal

Table 2 : Material properties used in calculations and results

Piezoelectric material	PZT-5H
Young's modulus (GPa)	2
d_{31} (pC/N)	-274
d_{32} (pC/N)	-274
d_{33} (pC/N)	593
e_{33} (nC/m)	30.1
Density (Kg/m ³)	7500
Speed of sound (m/s)	2500
Electromechanical coupling factor K	0.39
Rail structure	Steel
Young's modulus (*10 ¹⁰ pa)	20
Density (Kg/m ³)	7800
Speed of sound (m/s)	5960
Lame elastic moduli λ (*10 ¹⁰ pa)	-11.58
Lame elastic moduli μ (*10 ¹⁰ pa)	-7.99
Murnaghan 3 rd order elastic constant 1 (*10 ¹⁰ pa)	-24.8
Murnaghan 3 rd order elastic constant m (*10 ¹⁰ pa)	-62.3
Murnaghan 3 rd order elastic constant n (*10 ¹⁰ pa)	-71.4

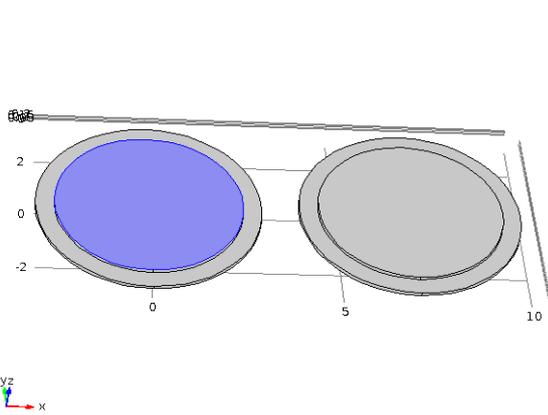


Fig. 9. Floating Terminal

The top and bottom layers of piezoelectric sensor has electrode on its faces which can be ignored due to their low thickness. Hence are not considered in geometry. The electronic behavior of electrodes are considered and modeled with the electrostatic boundary condition of the piezoelectric sub-domain. The upper face of the PZT is grounded and floating condition is applied at the lower surface.

V. SIMULATION OF SENSOR AND RESULTS

A. Physics Applied

Three different physics are applied to simulate the designed geometry and as follows;

1. Solid Mechanics: This physics is used to measure vibrational behaviors of acoustic waves inside the rail track and then passing these waves to piezoelectric sensors. Pw1 signal is applied as boundary load.
2. Electrostatic: This physics is used to measure the potential difference between ground and floating terminals of sensors. The acoustic pressure generated by pw1 waves produces deformation in piezoelectric crystal and as a result voltage is developed at floating terminals.
3. Electric Circuit: This physics is used as interaction between electrostatic and electrical circuits. The piezoelectric sensors are working as voltage sources and connected with circuit using external I Vs U1 link.

B. Transient Analysis

This section is used to describe the transient analyses conducted on the model. The applied pressure is 3×10^5 Pa (transient input) is applied for 20s at the boundary load. This is acoustic input to the model. This wave is a function of time $pw1(t) = P0 \cdot \sin(2 \cdot \pi \cdot f \cdot t)$ and a piecewise function $pw1(t)$ is used to plot the wave as shown in Fig. 10. Description of time and pressure symbols used to plot wave is given in table 3.

Table 3 Description of time and pressure in wave formation

Name	Expression	Description
t0	20[s]	Duration of time
P0	3e5[Pa]	Applied Pressure

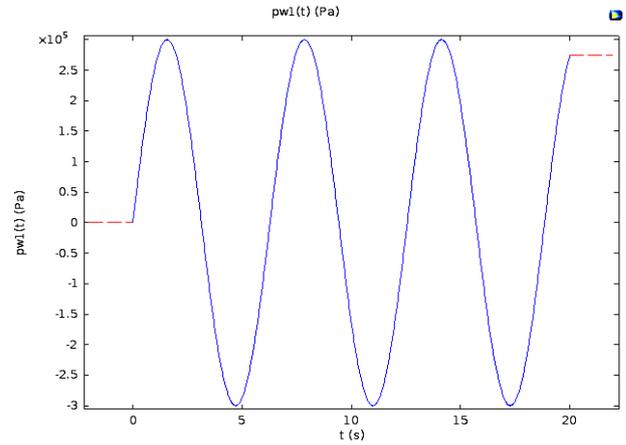
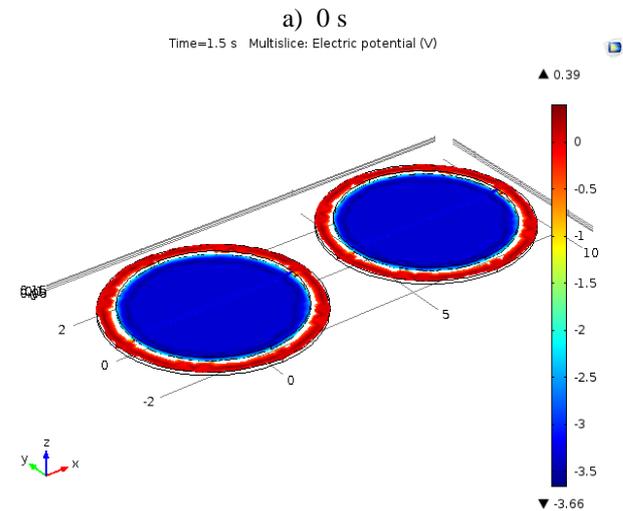
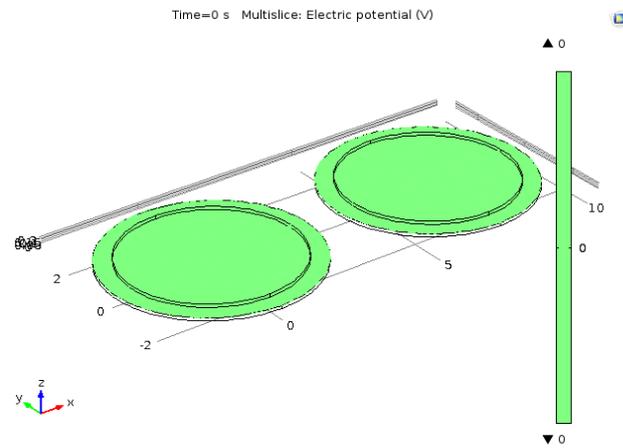
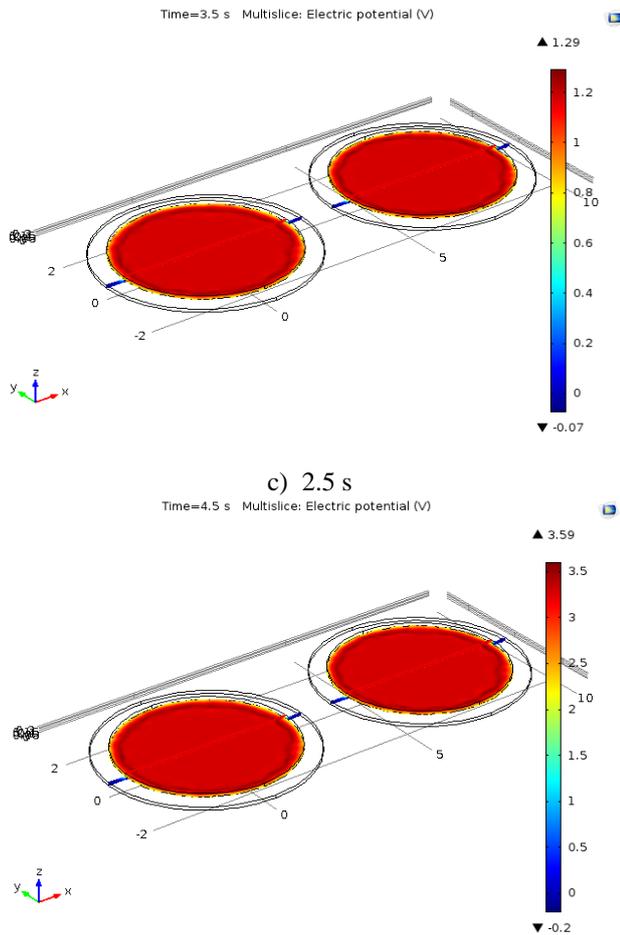


Fig. 10. Applied Pressure wave for 20 s

Two functions (es.fp1.V0 and es.fp2.V0) are used to compute voltages across piezoelectric devices and measured voltages are shown in Fig. 11.



b) 1.5 s



d) 4.5 s

Fig. 11. Electrical potential generated at a) 0 s b) 1.5 s c) 3.5 s d) 4.5 s

Two functions es.fp1.v0 and es.fp2.v0 are used to compute voltages across both the piezoelectric devices. The first function across device 1 is then fed to rectifier circuit as shown in Fig. 4 (a) and output is plotted in Fig. 12. Here it is very clear that the output of piezoelectric devices can easily be converted into the dc voltage.

When both the functions are used together in series, it is clearly shown in Fig. 13 that output response is additive in nature. Hence it is possible to use more number of piezoelectric devices to generate suitable power as per application needs.

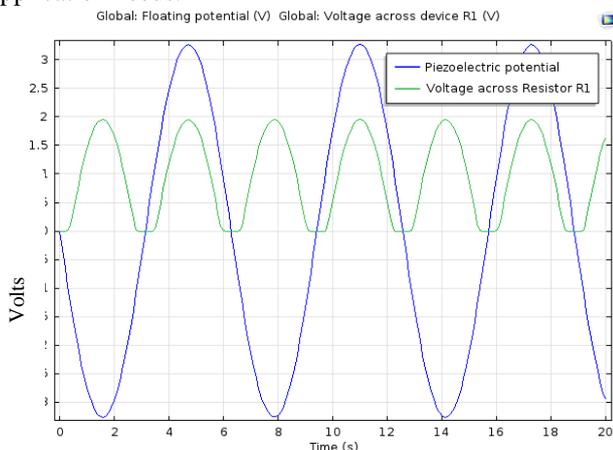


Fig. 12. Electrical potential across load resistance R1 Vs voltage across single PZT-5H

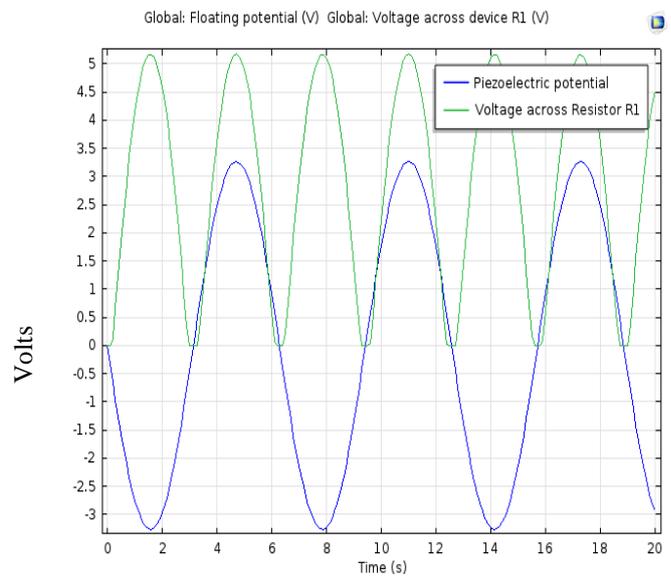


Fig. 13. Electrical potential across load resistance R1 Vs voltage across double PZT-5H

CONCLUSION

COMSOL multiphysics software is powerful tool to simulate and analyze a model. It is effectively used to model a structure for wave propagation and its characteristics are studied. These waves are then used to harvest energy from railway tracks with the help of piezoelectric sensors. The addition of semiconductor and electrical circuit in version 5 of COMSOL enhanced the capability of software for better understanding of problem in hand in interaction with electric circuit behavior.

Various geometries are designed and are simulated in COMSOL software and it is concluded that single piezoelectric device has generated alternating electric potential. This can easily be converted into dc voltage by the use of rectifier circuit. Further it is also evident that more number of piezoelectric devices connected in series or a array of piezoelectric devices can be used to develop more power suitable for different types of applications.

Batteries can be used to harvest the energy produced at the output of sensors. This can solve the problem of power requirement for lights at dark places near tunnels, platforms and other surroundings near to railway crossings. This study can also be used to design a device which is self powered like self powered warning instruments for railway staff working at railway tracks for maintenance purposes.

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