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HYBRID ENERGY HARVESTING
FROM A VEHICLE SUSPENSION
SYSTEM

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Abstract: The ever-increasing population has led to a growing need for clean energy and vehicle transportation. The majority of fuel energy is lost in the suspension system of road-bound automobiles. Vibration energy is the most significant portion of energy lost in vehicles. In this work, two technologies are being explored for harnessing vibration energy: electromagnetic induction and piezoelectric energy harvesting. A vibration sensitive device is designed using permanent magnets and piezoelectric strips using simulation model to harness vibration energy with the combination of piezo-electromagnetic hybrid energy harvesting. Simulation of cantilever beam under vibration is developed using COMSOL Multi-physics tool. The parametric analysis is performed with a simulation model. A prototype model is developed to validate with the simulation results. Results indicate that around 3.7V of voltage is extracted for 3Hz dominant frequency of vibration. The integration of piezo-electromagnetic harvester enhances the overall output power and efficiency. The harvested energy can be used to charge batteries and power the electronic systems of the vehicle.

Keywords: Energy Harvesting, Electromagnetic, Piezoelectric, Vibration

1. Introduction

The world is a reservoir of energy. It is widely recognized that energy cannot be created or destroyed; it can only be converted from one form to another. Electrical energy is among the most prevalent kinds of energy, making the effective and sustainable extraction of this energy from both conventional and unconventional sources a significant topic of research. In recent years, energy harvesting from vibrations has emerged as a highly promising technology, primarily due to the large variety of frequencies available that remain inefficiently employed. This research entails the creation of a hybrid system containing piezo and electromagnetic energy harvesting to extract vibrational energy from automotive suspension, which is entirely

clean and dependable. The configuration utilizes basic hardware components, rendering it economical.

In recent years, prolonging battery lifespan has emerged as a significant issue for various applications, including wireless sensor nodes, medical implants, and low-power wearable devices. Research on harvesting energy from the environment is prevalent due to the technological challenges and high costs associated with replacing primary batteries in specific applications. Among the diverse energy sources in nature, environmental vibration has garnered significant interest from researchers owing to its accessibility, minimal utilization constraints, environmental abundance, and the presence of uncomplicated power generation mechanisms. The vibration energy harvesting method can utilize one of three transducer mechanisms: piezoelectric, electromagnetic, or electrostatic. A piezoelectric energy harvester produces electrical energy by the internal creation of electric charge when subjected to time-varying strain in a piezoelectric material. Vibration applied to a moveable component of a capacitor in the electrostatic energy harvester creates capacitance variation and generates power with the assistance of a polarization source. An electromagnetic energy harvester employs variations in magnetic flux connected to the coils to generate electric current. Electromagnetic energy harvesting is a compelling option for vibration energy harvesters because of its simple mechanism for converting the relative motion between a magnet and a coil into electrical energy, as well as its capacity to deliver relatively high output power. The integration of an electromagnetic transducer with a piezoelectric transducer forms the foundation of the project aimed at efficiently harvesting vibrations generated in the automotive suspension system to sustainably charge the battery while in motion and extend its lifespan. This concept concentrates on vibration harvesting from automotive suspension but may be adapted to capture both low and high-frequency vibrations from the environment by modifying the design parameters.

The complete vibration harvester apparatus can be categorized into two components: electromagnetic and piezoelectric transducers. The design of electromagnetic energy harvesters commonly employs a spring-mass-damper arrangement to support the proof mass. The device converts external vibrations into relative motion between the permanent magnet and coil by utilizing a spring element to support either the magnet or the coil; however, this project presents

an electromagnetic vibration energy harvester that employs the linear motion of a springless proof mass. The intrinsic characteristic of vibrational energy to generate linear motion is being maximally utilized in this linear electromagnetic energy harvester. A series of rectangular magnets oscillates laterally without traditional spring support due to external vibrations, generating a time-varying magnetic field for an array of coils positioned beneath the channel. Ferrofluid has been utilized as a lubricating agent between the magnets and the underlying channel to enhance the movement of the magnetic array while minimizing friction. This gadget, sensitive to electromagnetic vibrations, is affixed to a cantilever beam composed of piezoelectric crystals. This cantilever beam produces electrical energy through the internal creation of electric charge when time-varying strain is applied to the piezoelectric material due to vibrations and the mass of a vibration-sensitive gadget positioned at its tip.

The vibration energy harvesting system maximizes the vibrations generated by automotive suspension, rendering it both efficient and sustainable for battery charging. Positioning the vibration-sensitive device near the tip of the cantilever beam is advantageous, as the cantilever beam enhances the frequency of mechanical vibrations received from the suspension system, thereby functioning as both a piezoelectric transducer and a frequency amplifier for mechanical vibrations. Consequently, the amalgamation of two vibration energy harvesting technologies renders this configuration effective in capturing vibrations from the automotive suspension system.

The piezoelectric cantilever beam, in conjunction with the electromagnetic vibration energy harvesting device functioning as an inertial mass, is affixed to the automobile's suspension system at a suitable spot. The positioning of this configuration within the suspension system changes according to the type of suspension employed in the vehicle. The aforementioned flow diagram illustrates that vibrations in the suspension system are transmitted to the mechanical apparatus. The piezoelectric cantilever beam produces electrical energy through the internal creation of electric charge when time-varying strain is applied to a piezoelectric material as a result of vibrations and the mass of a vibration-sensitive device positioned at its tip. The mass of the cantilever beam is inferior to that of the electromagnetic energy harvesting device, resulting in amplified vibrations near the beam's tip. The amplified vibrations induce oscillation of the

magnetic array above the aluminium channel, generating a time-varying magnetic field for an array of coils situated underneath the channel. Consequently, electromotive force is generated in the coil. The outputs from both transducers are alternating and exhibit peaks. In power electronic circuits, outputs from transducers are combined to produce a singular output, which is then supplied as input to a completely controlled rectifier. The rectifier's DC output is subsequently supplied to a boost converter, where the voltage is elevated and directed to the battery.

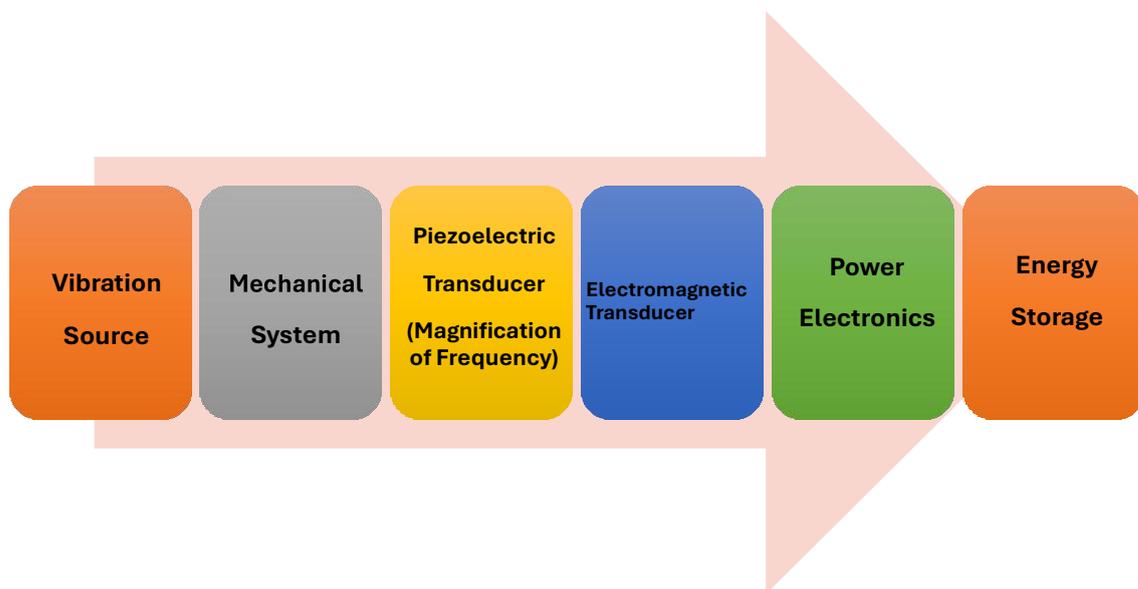


Figure 1: Energy Harvesting Systems from Automotive Systems

The effort aims to create an effective and sustainable vibration harvesting system to utilize vibrations generated by the automotive suspension system as in Figure 1. The electromagnetic transducer design employed in this research diverges from the conventional magnet and coil configuration or axial flux rotary power generator. The project aims to achieve maximal displacement of the proof mass through a springless system, wherein the proof mass is not supported by a spring element and can move freely within a limited channel or hollow, exhibiting regular motion under external vibrations. This device is engineered to function as a linear generator, harnessing the intrinsic property of vibrations to enable linear motion of objects for

optimal power generation. While vibrations derived from automotive suspension are the focal point of the research, vibration energy from alternative sources can also be effectively captured, contingent upon suitable modifications in dimensions and orientation of the system. This can be achieved by performing research, analyzing various sources of vibrations, and finding the contexts in which this configuration can be utilized.

The significance of this research can be summed up as follows:

1. This research is an integration of two distinct transducer technologies namely piezoelectric and electromagnetic.
2. The setup has a simple design and is easy to install.
3. Low investment and maintenance cost.
4. Efficient and occupies very less area for installation.
5. Makes use of abundantly available vibration energy which is generally wasted.
6. The permanent magnets have a long life.
7. The setup can charge automobile battery on the go and increases lifetime of battery.

2. Literature Review

The extraction of energy from car suspension systems has garnered interest owing to the demand for sustainable energy solutions within the automotive sector. Vehicle suspensions, which absorb vibrations from the road, dissipate energy as heat. Transforming this usually squandered mechanical energy into electrical energy has the potential to enhance vehicle economy and diminish dependence on external power sources. Hybrid energy harvesting systems that integrate piezoelectric and electromagnetic technologies have emerged as a viable solution to accomplish this objective. This literature review examines contemporary research trends, design techniques, and problems related to piezo-electromagnetic hybrid energy harvesting from car suspension systems.

Piezoelectric materials produce electricity when exposed to mechanical stress. In car suspensions, piezoelectric materials can be integrated into shock absorbers, tires, or other suspension elements to capture energy from vibrations induced by road irregularities. Numerous studies have investigated the viability of employing piezoelectric materials for energy harvesting in cars.

Sodano et al. (2004) were pioneers in examining the application of piezoelectric materials in car suspension systems. The piezoelectric transducer was shown to generate a modest amount of power from suspension vibrations. Subsequent research concentrated on enhancing power output by superior material selection, arrangement, and integration into vehicle constructions. A crucial determinant affecting piezoelectric energy harvesting is the frequency and amplitude of vibrations. Alshaer and Zaman (2014) investigated the impact of different road profiles and vehicle velocities on the energy collecting capability of piezoelectric devices in suspensions. Their research indicated that low-frequency vibrations, commonly encountered in actual driving scenarios, can generate useable energy when integrated with appropriate piezoelectric materials and designs.

Recent advancements in piezoelectric materials, including lead zirconate titanate (PZT) and polyvinylidene fluoride (PVDF), have facilitated enhanced energy conversion efficiency. Researchers such as Moazzeni et al. (2020) have investigated nanostructured piezoelectric materials, which provide enhanced mechanical flexibility and superior strain-to-energy conversion efficiencies. These advancements have resulted in the production of piezoelectric devices capable of generating increased power from the comparatively low-frequency and low-amplitude vibrations in car suspensions.

Electromagnetic energy harvesting entails the transformation of kinetic energy into electrical energy via electromagnetic induction. In automobile suspensions, this is generally accomplished by positioning a magnet and a coil in relative motion, either integrated inside the suspension strut or in conjunction with the spring and damper system. The relative movement between the magnet and coil generates an electric current, which can then be utilized to charge batteries or power small electrical components within the vehicle.

Preliminary investigations into electromagnetic energy harvesting from suspensions concentrated on developing efficient devices that reduce energy losses while enhancing power output. Suda and Shiba (1996) were innovators in this field, introducing a regenerative suspension system that employs electromagnetic damping to simultaneously harvest energy

and enhance ride comfort. Subsequently, various studies have enhanced the design and control methodologies for electromagnetic harvesters in vehicular suspensions.

Zhang et al. (2015) distinguished themselves by developing a bi-directional electromagnetic energy harvester incorporated into the suspension system of an electric car. Their technique could recuperate a substantial amount of vibrational energy, especially under adverse driving circumstances. Nonetheless, they observed that the dimensions and mass of the electromagnetic components may restrict the feasible implementation of such systems in mass-manufactured vehicles.

Recent improvements in electromagnetic energy harvesting have concentrated on enhancing the compactness and efficiency of the systems. Cheng et al. (2018) created a dual-mode electromagnetic energy harvester capable of alternating between high-frequency and low-frequency harvesting modes based on the driving parameters. This adaptability enables the device to extract energy more effectively across a wider spectrum of vibration frequencies and amplitudes.

Nakano presented a ball-screw electromagnetic damper for energy regeneration from an active vehicle cabin suspension system, utilizing that energy to power the system, so becoming it entirely self-sufficient. The article evaluates the viability of the system's self-sufficiency by analyzing the equilibrium between the energy regenerated and the energy consumed by the system. The electromagnetic damper model employed in this work comprises a DC motor, a ball screw, and a nut. The linear movement of the damping system induced by environmental vibrations is transformed into rotational motion through the ball-screw and nut arrangement. The rotational motion imparted to the motor causes a voltage that generates a current, which is stored in an electric double layer capacitor as electrical energy. The energy-regenerative damper and the actuators, situated at the front and back suspensions of the truck, are linked to the same capacitor via relay switches. The circuits linking the actuators incorporate variable resistors controlled by an external computer. This enables the regulation of electric current to achieve a desired continuous motor force, rendering the damping mechanism entirely operational. Simulations conducted indicated that the average regenerated and absorbed energy during a

duration of 20 seconds was 31.63 W and 55.39 W, respectively. This resulted in an efficiency of 36%.

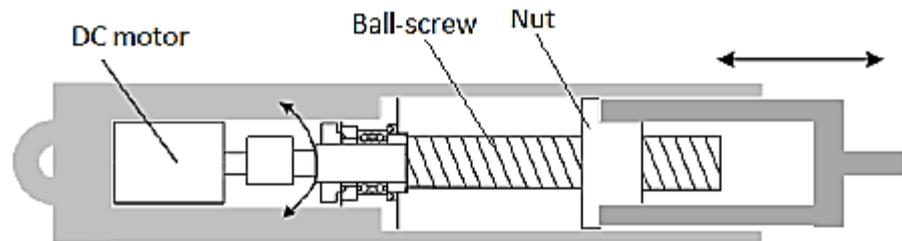


Figure 2: Linear Electromagnetic Energy Harvester

The linear electromagnetic energy harvester as in Figure 2 converts the kinetic energy of linear motion into electrical energy using a permanent magnet generator. The magnet assembly typically consists of permanent magnets and coils. To achieve optimal regeneration, it is essential to optimize the magnetic flux density within the coils. The current in the coil is generated by the relative motion between the magnets and the coils. Maximizing magnetic flux can be achieved by utilizing highly permeable materials to reduce the reluctance of magnetic circuits. Zuo et al. developed and evaluated a regenerative shock absorber configured as a linear generator. A crucial element of the regeneration system is the phase during which the coils in the linear energy harvester are situated. All adjacent coils are phased 90 degrees apart, resulting in each pair of four coils forming a four-phase structure. The linear energy harvester comprises four sets, totalling 16 coils. The four-phase layout ensures a more uniform regeneration of energy, with one pair of the setup consistently aligned with the magnetic loops.

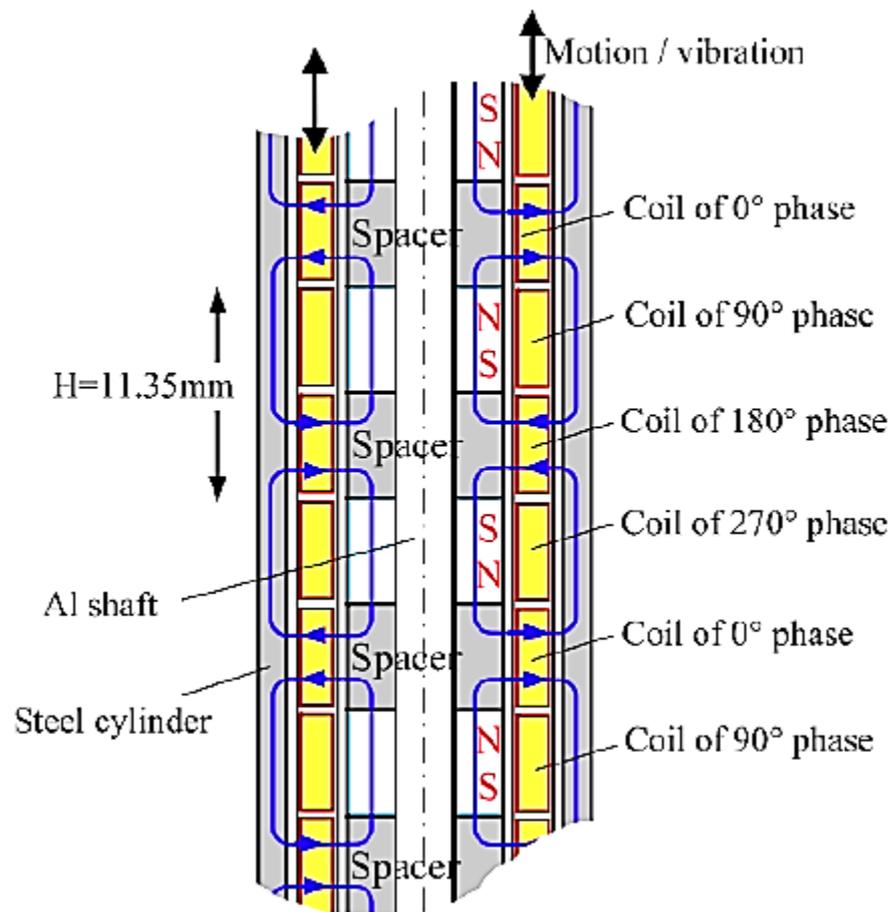


Figure 3: Basic axial flux rotary generator

The design of the electromagnetic vibration energy harvester device utilized in this research is derived from the concept of a basic axial flux rotary generator as in Figure 3. The latter features a stator and rotor with a disc configuration, wherein the magnets are arranged to align the manufacturing flux with the common axis of the rotor and stator. The rotor of an axial flux generator is often affixed to a shaft that is supported by ball bearings, which preserve the minimal space between the magnets and copper windings to optimize output power. The design of the electromagnetic vibration energy harvester employs linear motion rather than rotational motion to harness external linear vibrations and ensure a straightforward structure. The minimal distance between the winding and the magnet array is determined by the thickness of the bottom section of the aluminium enclosure. Lubricating the

channel with ferrofluid diminishes friction and wear at the interface between the magnet and the aluminium housing. Furthermore, the necessity for exact regulation of the spacing between the rotor and winding can be eliminated.

3. Mathematical Model and Design of Piezo – Electromagnetic Hybrid Energy Harvester

3.1 Mathematical Model of Automobile Suspension System:

The automobile's suspension system is linked to the wheels, facilitating contact between the vehicle and the road. The suspension system's function is to absorb shocks transmitted to the vehicle from potholes or bumps encountered by the wheels, thereby safeguarding the automobile's mechanical components and enhancing driving comfort. The wheels oscillate vertically as they traverse over depressions and elevations on the roadway. The suspension system inhibits wheel vibrations from transmitting to the vehicle's body, hence preventing erratic body movements. The mechanical representation of a quarter car suspension system is illustrated here in Figure 4.

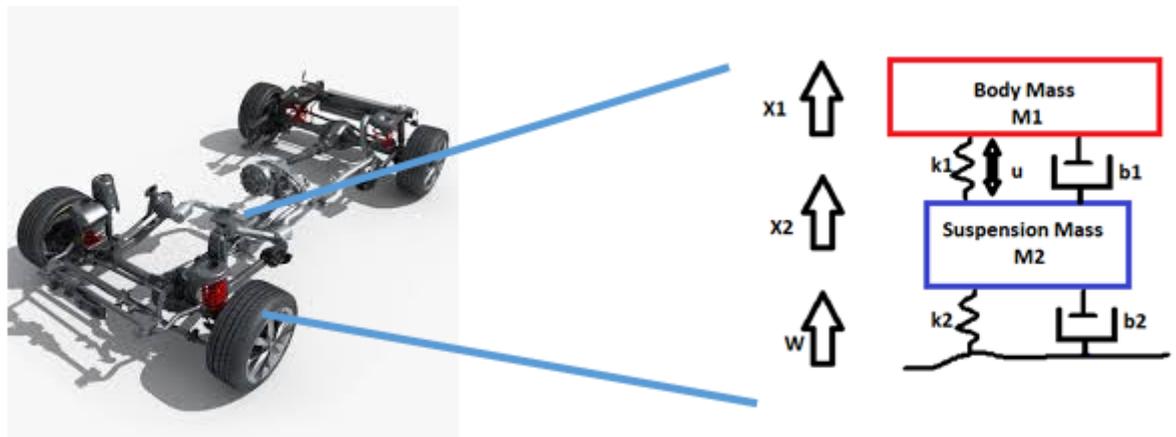


Figure 4: Mechanical model of suspension system

M1: 1/4 car body mass

M2: suspension mass

k1 : spring constant of suspension system

k2 : spring constant of wheel and tire

b1 : damping constant of suspension system

b2 : damping constant of wheel and tire

U is the controlling force and W is the force acting on the suspension system from the uneven road. The initial value condition is considered to be zero for simplicity of analysis. Solving the mechanical model in Laplace domain we get,

$$\begin{aligned} [(M_1s^2 + b_1s + k) * x_1] - [(k_1 + b_1s) * x_2] &= u \\ [M_2s^2 + (b_1 + b_2)s + (k_1 + k_2)] * x_2 - [(b_1s + k_1) * x_1] &= -u + [(b_2s + k_2) * w] \end{aligned}$$

Representation of the above equations in matrix form,

$$\begin{bmatrix} (M_1s^2 + b_1s + k) & -(k_1 + b_1s) \\ -(b_1s + k_1) & M_2s^2 + (b_1 + b_2)s + (k_1 + k_2) \end{bmatrix} \begin{bmatrix} x_1 \\ x_2 \end{bmatrix} = \begin{bmatrix} u \\ -u + [(b_2s + k_2) * w] \end{bmatrix}$$

Transfer function is given by:

$$G_1(s) = \frac{x_1(s) * x_2(s)}{U(s)} = \frac{(M_1 + M_2)s^2 + b_2s + k_2}{\Delta}$$

$$G_2(s) = \frac{x_1(s) * x_2(s)}{W(s)} = \frac{-M_1 b_2s^3 - M_1 k_2s^2}{\Delta}$$

Here $G_1(s)$ is the transfer function considering the controlling force as input force and $G_2(s)$ is the transfer function obtained by considering the force from uneven road as input force.

3.2 Vibration analysis of suspension system

An automobile on a rough terrain exhibits bounce, pitch, and roll on top of its rigid body motion. In this analysis, a preliminary model for automobile's suspension system is assumed as presented in the Figure 5.

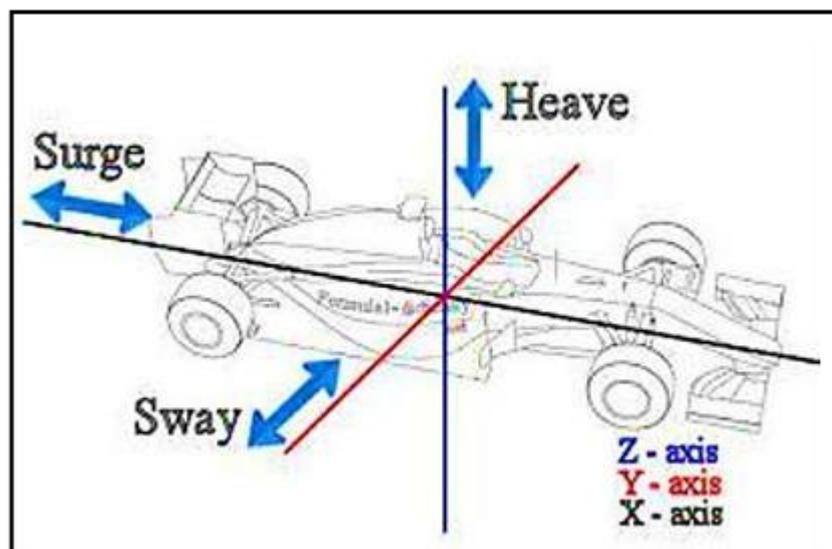


Figure 5: Model of Automotive Suspension Systems

SIMULINK model has been developed to analyse the vibrations in automobile suspension system. The vibrations have been analysed using the obtained transfer function under two scenarios, bounce and pitch. The translational motion of the automobile along the Z-axis is called bounce and the rotation of the automobile about X-axis is called pitch.

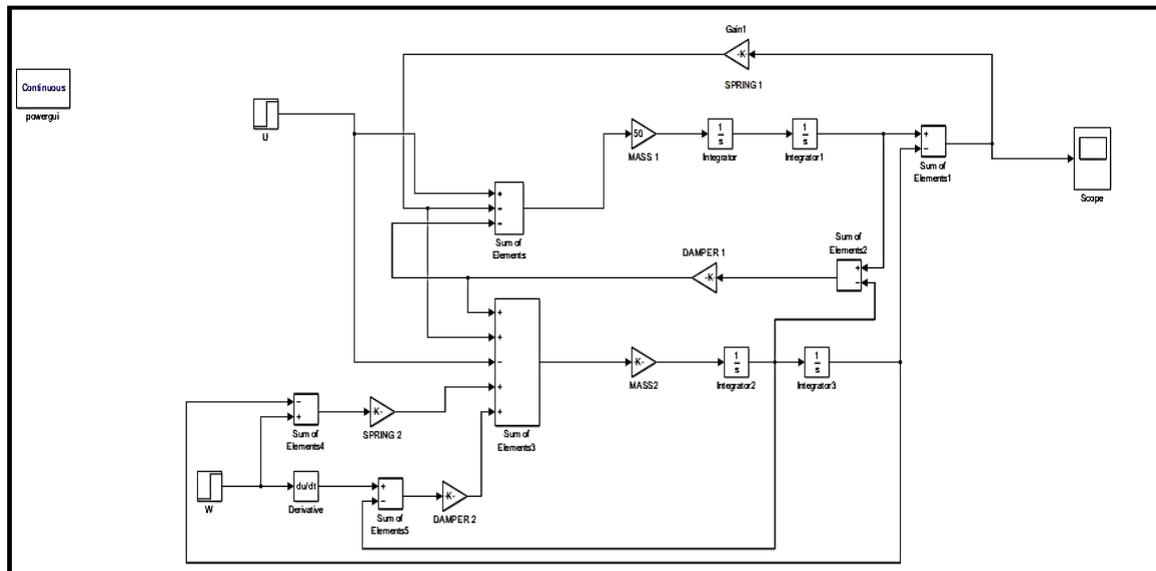


Figure 6 : Simulink model of suspension system

Amplitude vs. time graph of vibrations in automobile suspension system:

The amplitude vs. time graph of vibration in suspension system under pitch and bounce motion have been captured using Simulink. It can be observed that the vibrations in case of bounce have more amplitude and the suspension takes more time in damping this vibration in comparison to vibrations due to pitch motion.

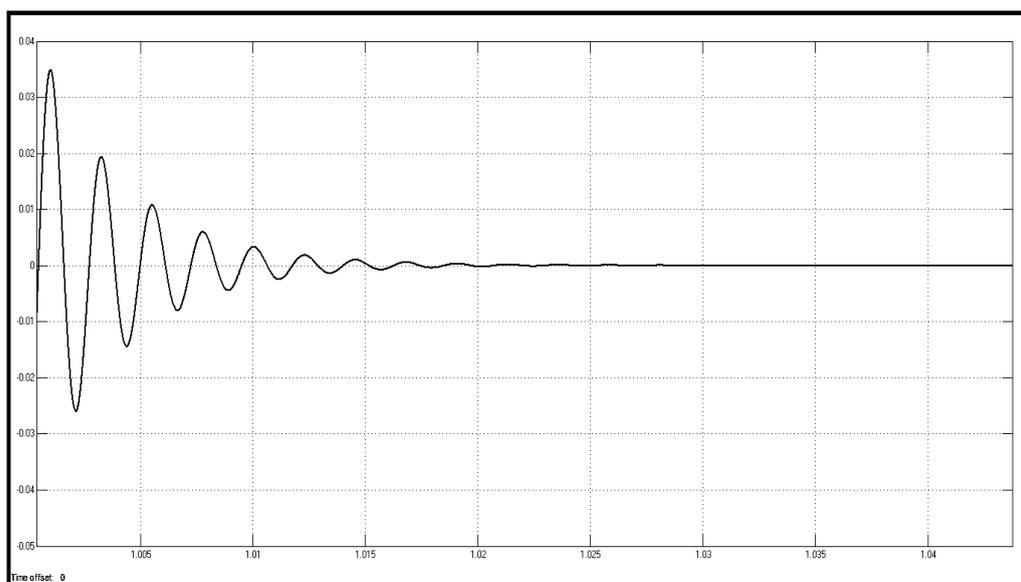


Figure 7 : Amplitude vs. time graph for pitch motion

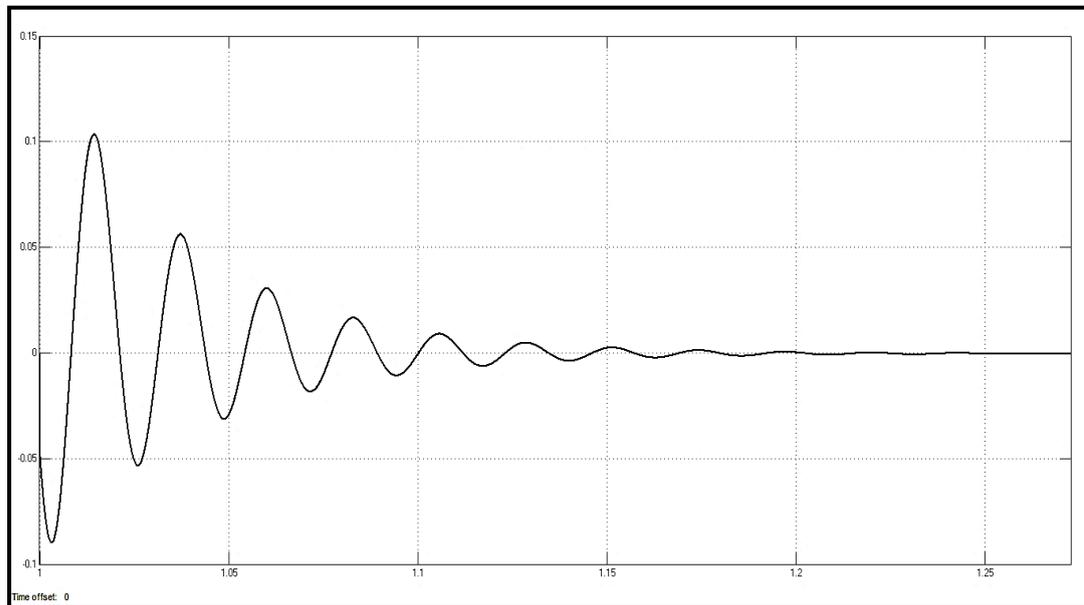


Figure 8 : Amplitude vs. time graph for bounce motion

3.3 Design of vibration energy harvester:

Vibration analysis of suspension system was performed in order to visualise the frequency and amplitude of vibration and interpret the maximum displacement the vibrations can cause to the magnetic array. After interpreting the displacement approximately, the design and dimension of electromagnetic vibration harvesting device and piezoelectric cantilever beam have been decided.

Design of electromagnetic vibration harvesting device:

The design of electromagnetic vibration harvesting device can be divided into two parts: a freely sliding magnet assembly and aluminum housing with fixed coils. A multi-pole magnet array composed of four bar magnets and a pole piece serves as proof mass moving inside the channel in response to external vibration. The pole piece covers the top side of the magnets, thereby enhancing the magnetic flux linking the coils placed under the

aluminum housing. An array of copper windings is fixed at five coil bobbins and connected in series. A minimum gap between the magnet array and coil is 2 mm, which is the minimum thickness of the aluminum housing underneath. As the magnet assembly is not supported by a spring element, magnet assembly makes constant impacts with the sidewall of the aluminum housing when external vibration is applied.

3D model of electromagnetic vibration harvesting device:

The 3-Dimensional design of the project was designed using software called CATIA. CATIA is an acronym of computer-aided three-dimensional interactive application. It is a multi-platform software suite for computer-aided design (CAD), computer-aided manufacturing (CAM), computer-aided engineering (CAE), PLM and 3D.

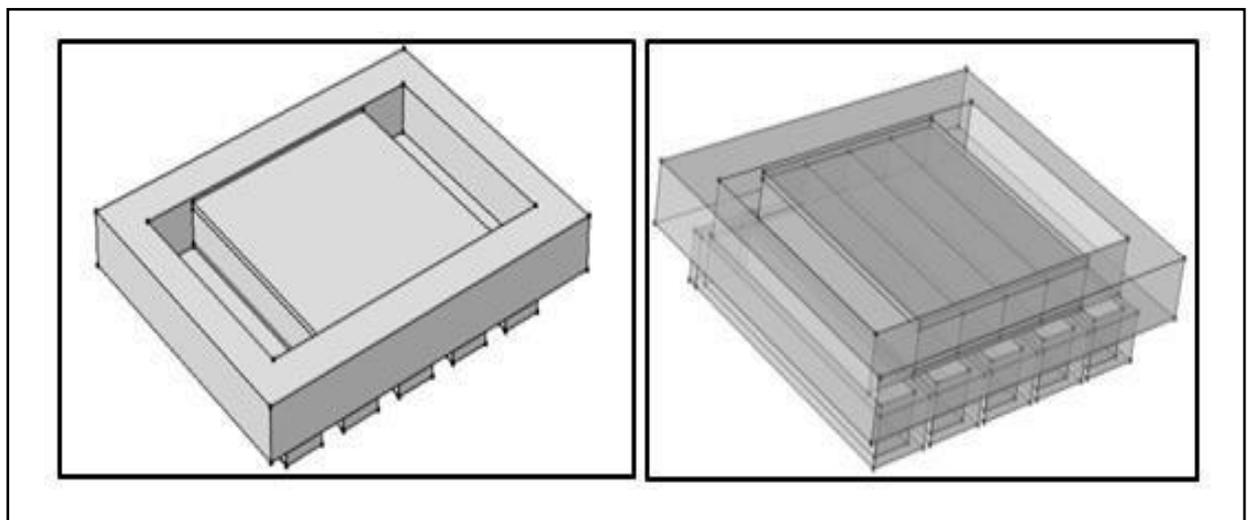


Figure 9 : Top view of the electromagnetic vibration harvesting device

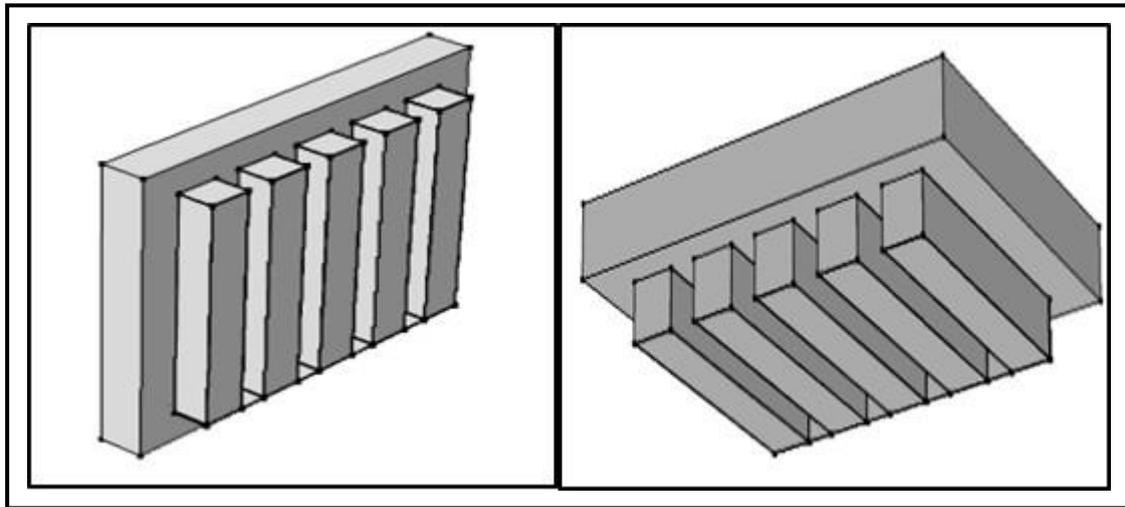


Figure 10 : Bottom and side view of the electromagnetic vibration harvesting device

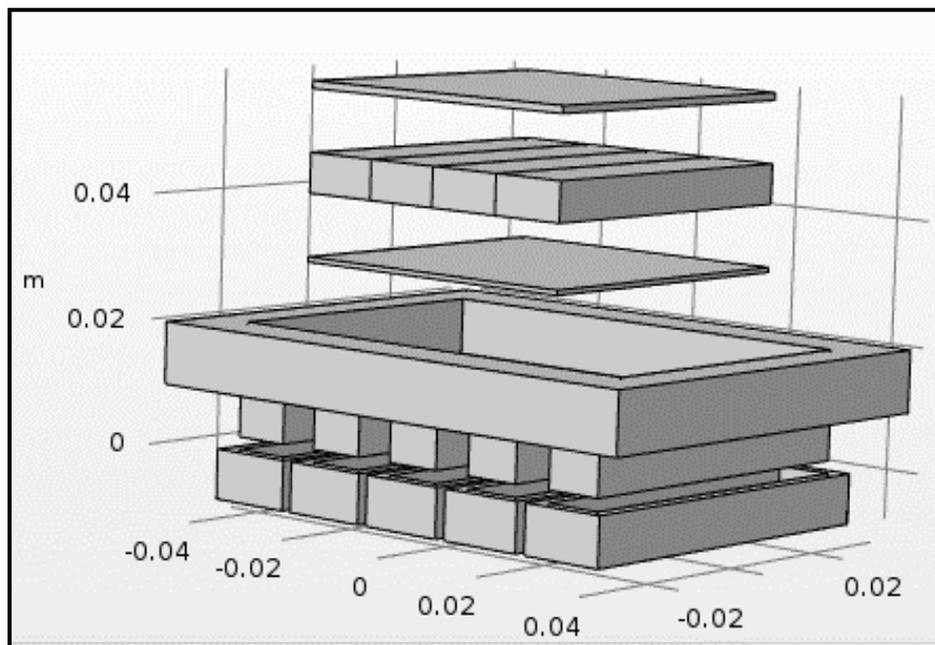


Figure 11 : Exploded view of the electromagnetic vibration harvesting device

Table 1 : Dimensions of 3D model of electromagnetic vibration harvesting device:

Component	Parameter	Value
Aluminium Housing	Inner length of casing	7.62cm
	Inner width of casing	5.58cm
	Inner height of casing	2cm
	Outer length of casing	9.22cm
	Outer width of casing	7.08cm
	Outer height of casing	2.2cm
	Winding slot length	5.61cm
	Winding slot width	1cm
	Winding slot length height	2cm
Iron plate	Length	5.08cm
	width	5.08cm
	Height	2mm
Magnetic array (4 magnets)	Length	5.08cm
	width	1.27cm
	Height	1.27cm
Ferrofluid	Thickness	1mm
Copper Winding (5 coils connected in series)	Diameter of wire	0.3mm
	Number of turns	140

Design of Piezoelectric vibration energy harvester:

Cantilever structure with inertial mass is the most widely used configuration for piezoelectric vibration energy harvesting device. In this project, the inertial mass used is electromagnetic vibration energy harvesting device. The length and thickness of the cantilever beam is designed based on the dimensions of the device.

3D model of piezoelectric vibration energy harvester:

The piezoelectric cantilever beam was designed using COMSOL Multiphysics. The cantilever beam structure two materials; Structural steel as substrate and Lead Zirconate Titanate (PZT-5A) as piezoelectric layers. The substrate material is in the middle position while PZT-5A is put top and bottom surface of the substrate.

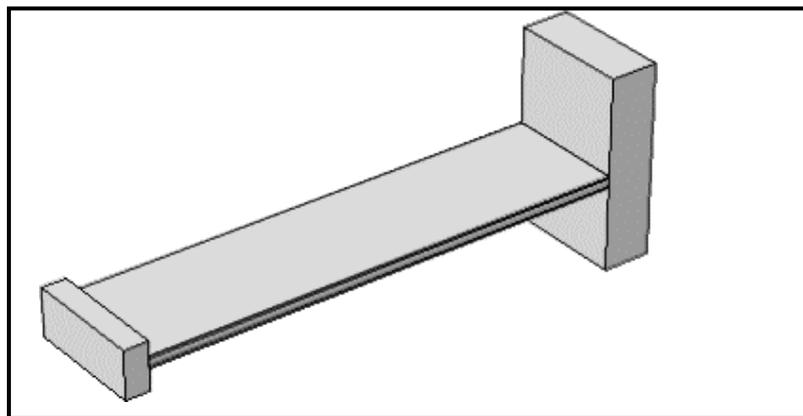


Figure 12 : 3D model of piezoelectric vibration energy harvester

Table 2: Dimensions of 3D model of piezoelectric vibration energy harvester:

Component	Parameter	Value
Cantilever beam made of Structural steel	Length	15cm
	thickness	3mm
	width	5cm
Piezoelectric strip (Top and bottom)	Length	0.5mm
	thickness	1.5mm
	width	0.5mm

Design and implementation of electromagnetic energy harvester prototype model:

The prototype model developed is used as proof of concept to test and validate the results. The dimensions and design of the prototype model is different from 3D model owing to its simplicity and budget constraints.

Table 3 Dimensions of prototype model:

Component	Parameter	Value
Aluminium Housing	Inner length of casing	5.5cm
	Inner width of casing	4cm
	Inner height of casing	0.7cm
	Outer length of casing	7.6cm
	Outer width of casing	5cm
	Outer height of casing	1cm
	Winding slot length	5cm
	Winding slot width	1cm
	Winding slot length height	1.5cm
Iron plate	Length	5cm
	width	2cm
	Height	1.2mm
Magnetic array (1 magnet)	Length	5cm
	width	1cm
	Height	0.5cm
Copper Winding (3 coils connected in series)	Diameter of wire	0.3mm
	Number of turns	60

The outer aluminium casing was done by drilling through a block of aluminium using Turrent milling machine shown in figure The pictures of the procedure and final outcome are shown below:



Figure 13 : Turrent Milling Machine



Figure 14 : Procedure carried out on milling machine

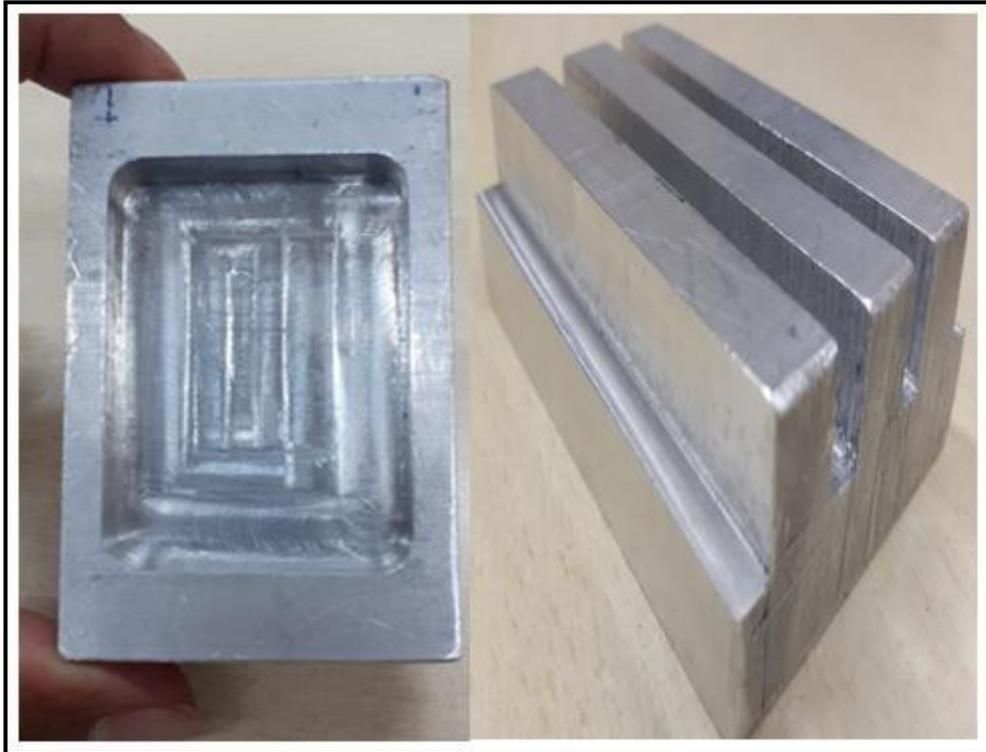


Figure 15 : Top and bottom view of the aluminium housing

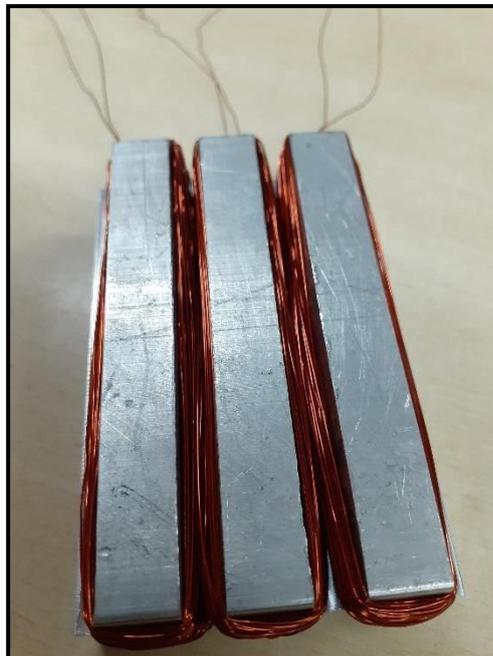


Figure 16 : Array of three coils connected in series

4. Simulation Analysis of the of Piezo – Electromagnetic Hybrid Energy Harvester

Simulations were conducted utilizing COMSOL Multiphysics. It is a cross-platform software for finite element analysis, solving, and multiphysics simulation. It facilitates traditional physics-based user interfaces and interconnected systems of partial differential equations (PDEs). COMSOL offers an integrated development environment and a cohesive workflow for electrical, mechanical, fluid, and chemical applications. Simulations have been conducted utilizing COMSOL Multiphysics. It is a cross-platform software for finite element analysis, solving, and multiphysics simulation. It facilitates traditional physics-based user interfaces and interconnected systems of partial differential equations (PDEs). COMSOL offers an integrated development environment and a cohesive workflow for electrical, mechanical, fluid, and chemical applications.

The flux density across the electromagnetic vibration energy collecting device has been measured using COMSOL Multiphysics. Flux density is defined as the quantity of magnetic flux passing through a unit area oriented perpendicular to the direction of the magnetic flux. The plot of magnetic flux density is illustrated below:

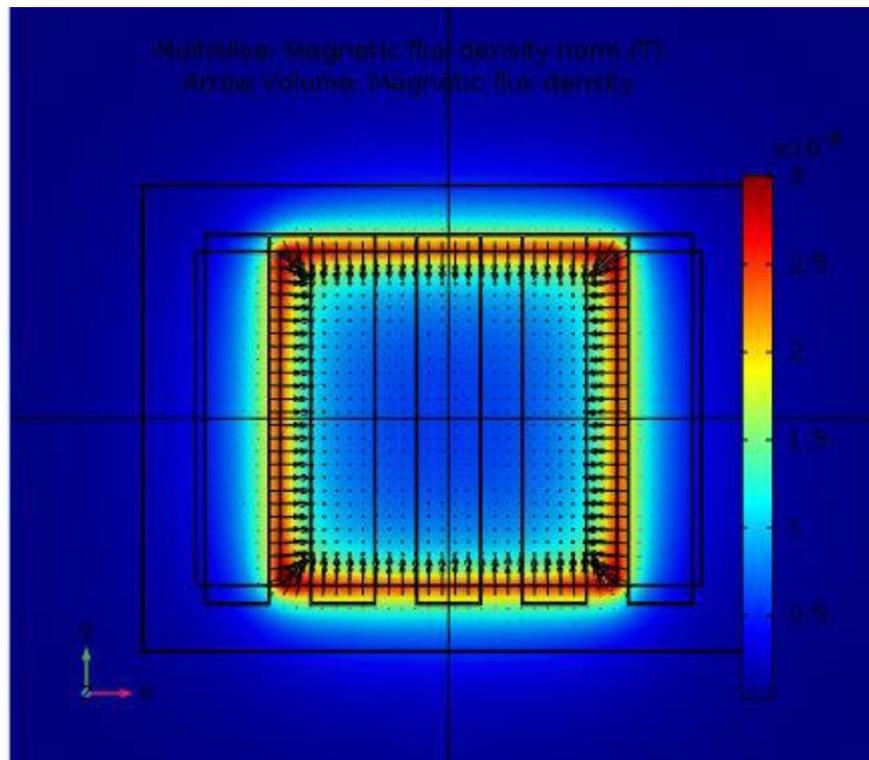


Figure 17 : Magnetic flux density contour

From the above plot it can be observed that the flux density is maximum towards the ends of the magnetic array. The magnetic flux lines have been shown in figure 18 and 19.

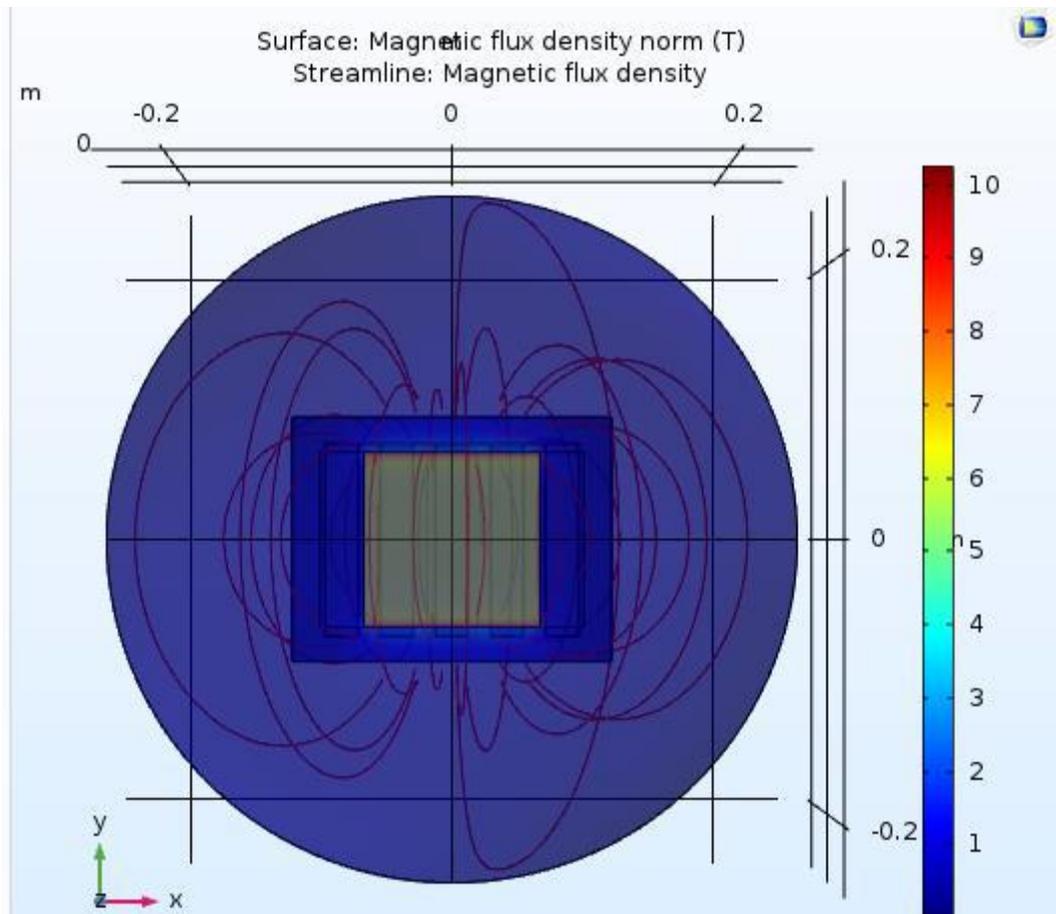


Figure 18 : Flux density and flux lines contour seen from top view

To make the analysis simple a 2D model of side view of the device has been developed.

The flux density plot of 2D model along has been shown below:

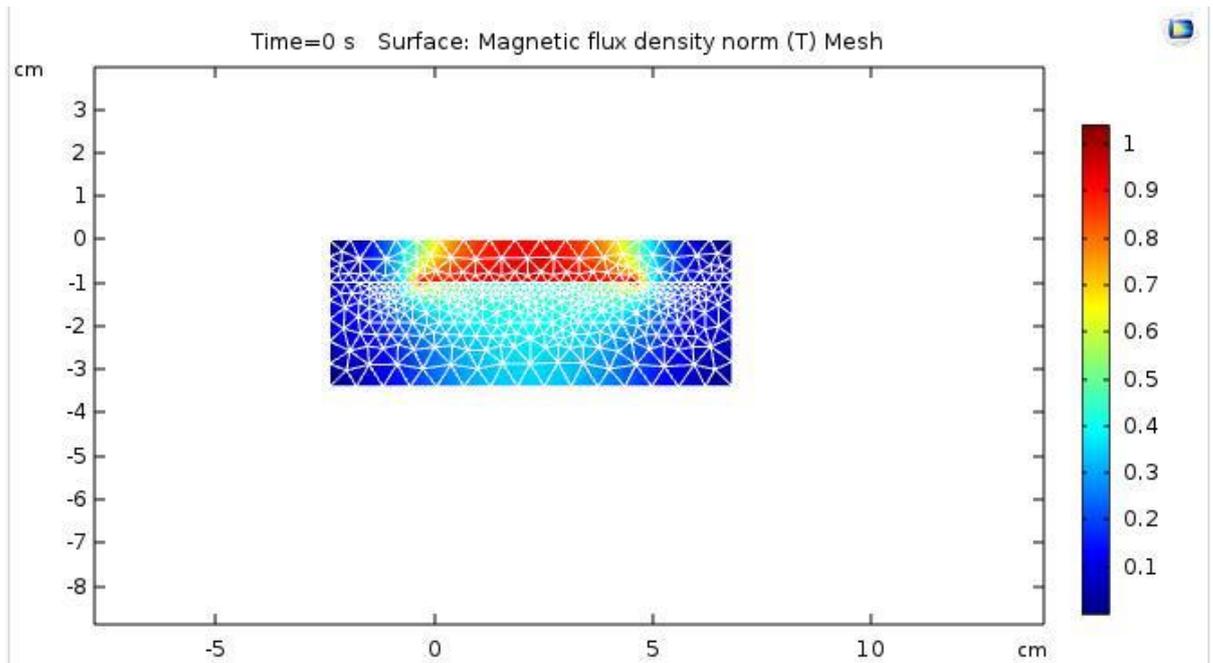


Figure 19 : Flux density plot contour of 2D side view of device

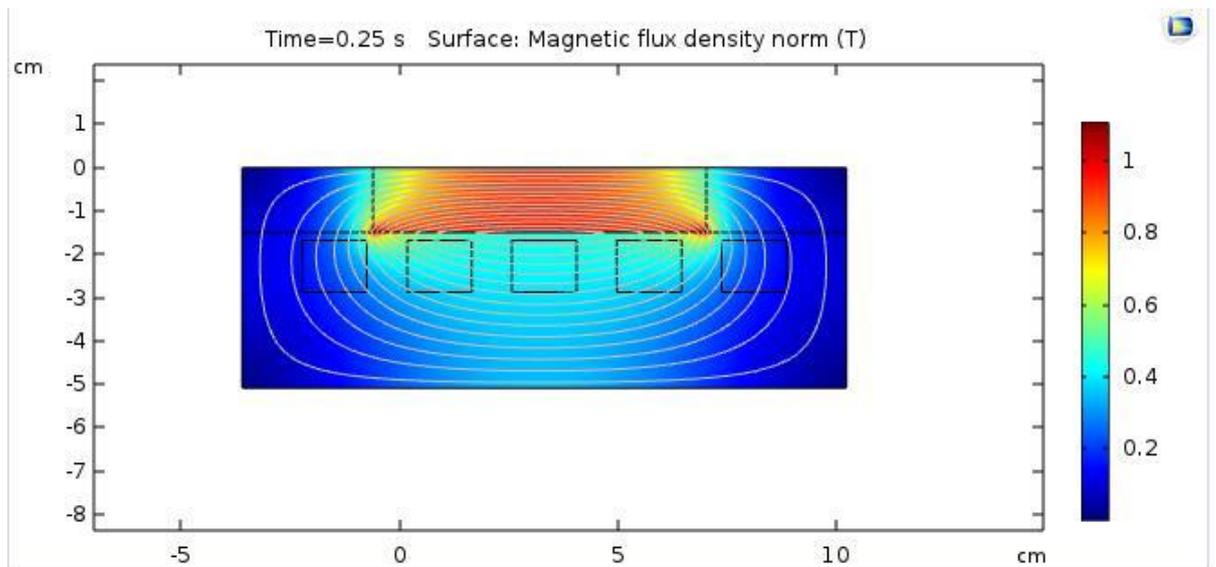


Figure 20 : Flux density and flux lines contour of 2D side view of device

To observe magnetic flux lines infinite boundary of air has been defined around the device. The oscillation of device in the presence of eternal vibrations results in time varying flux line passing though the copper magnet wire. Hence, inducing EMF in the coil.

A piezoelectric cantilever beam with an inertial mass generates output voltage when subjected to time-varying strain on the piezoelectric strip due to external vibrations.

Consequently, it is imperative to see the stress on the cantilever beam situated between two PZT-5A strips. The tension on the beam is graphically depicted in Figure 21.

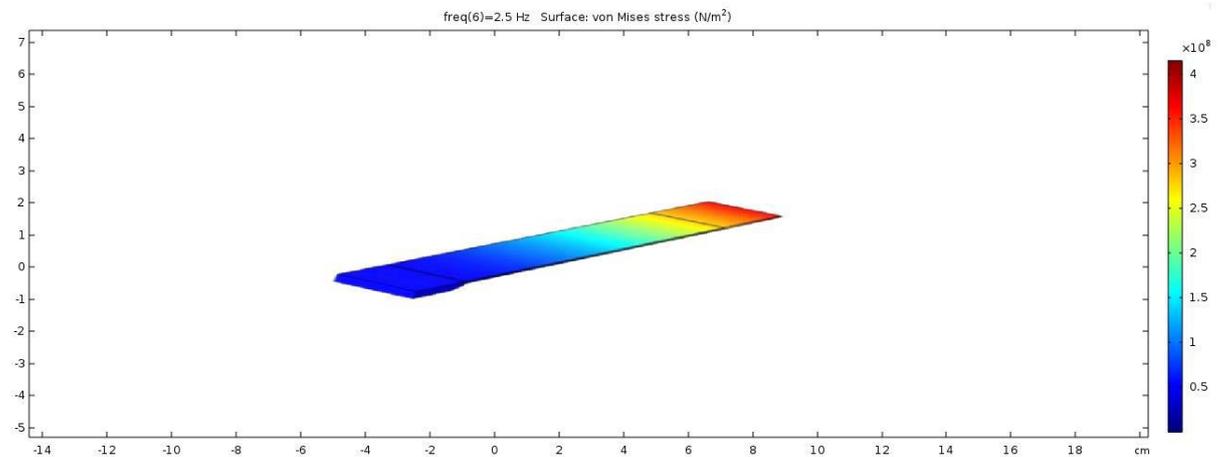


Figure 21: Surface stress contour of piezoelectric cantilever beam

From the above contour in Figure 21 it can be observed that the stress at the tip of cantilever beam is maximum due the presence of inertial mass, i.e. electromagnetic vibration energy harvesting device. This stress varies in the presence of external vibrations, resulting in generation of electrical energy.

5. Results and Discussion

Vibration energy harvesting from automobile suspension system is a project which indeed requires a lot of research, analysis and development. Simulations have been conducted using COMSOL Multiphysics. As a proof of concept, a prototype model has been developed as in Figure 23.

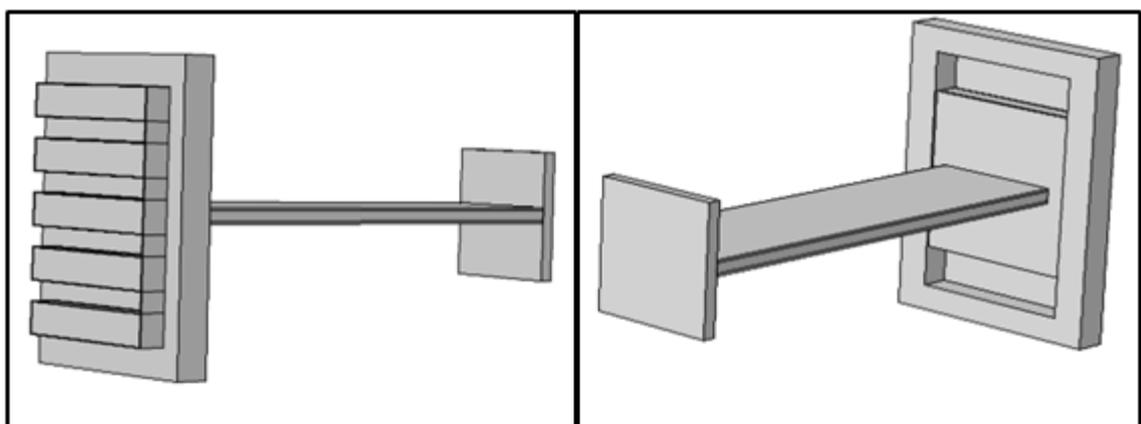


Figure 22: 3D model of assembled view



Figure 23 : Assembled view of prototype model

To obtain the output from the device, moving mesh (ale) physics has been used in COMSOL Multiphysics. The use of this physics can replicate the oscillation of magnetic array under external vibrations. These oscillations produce time-varying flux linking with the coil hence inducing EMF in the coil. The output voltage and current waveforms of the device have been captured in figure 24 and 25 respectively.

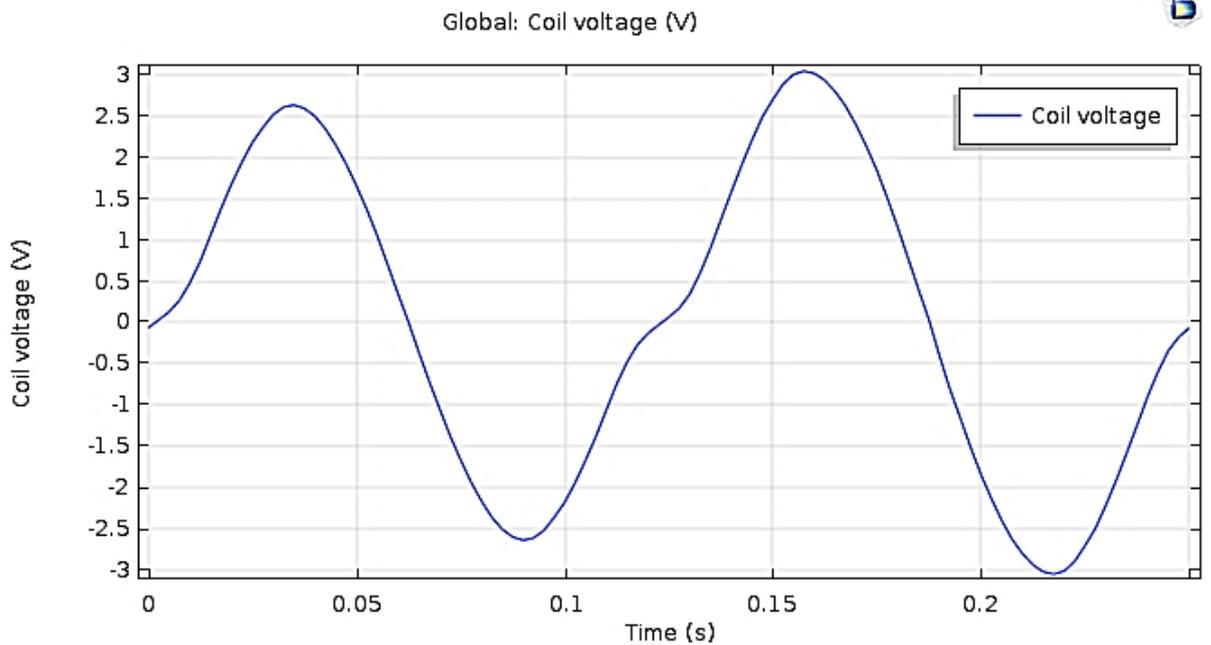


Figure 24 Voltage waveform of device

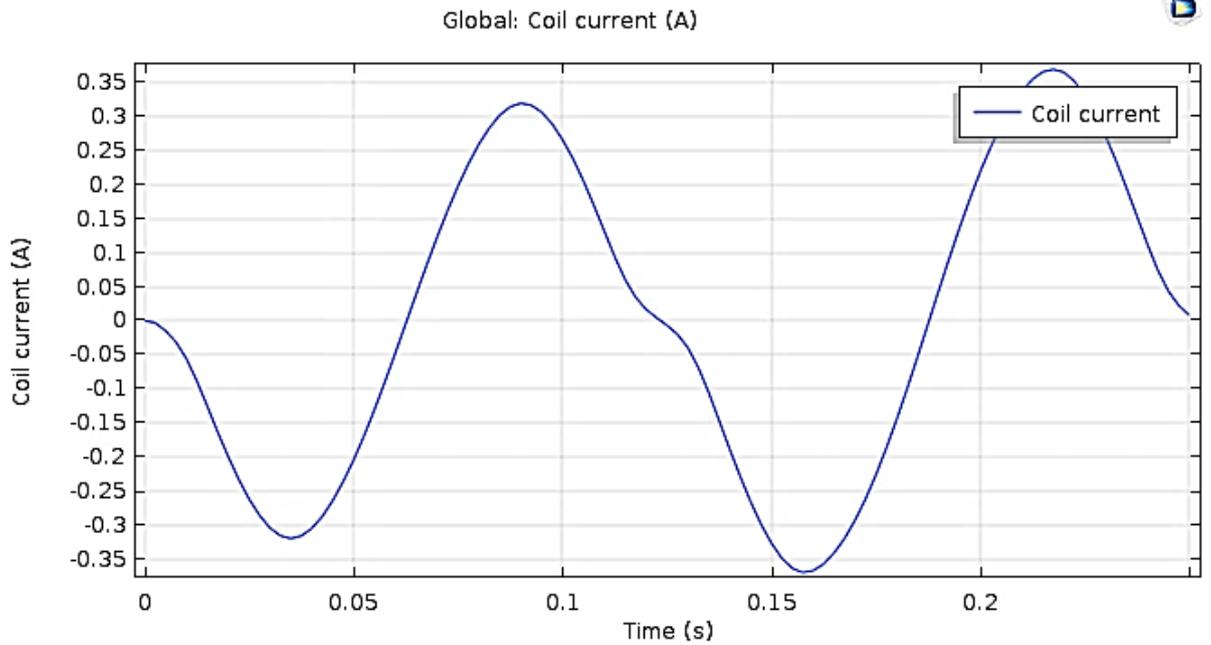


Figure 25 : Current waveform of device

Piezoelectric cantilever beam is attached to the automobile suspension and the other end has electromagnetic vibration harvesting device. Due to inertial weight there always exists stress on the beam and on application of external vibrations the stress on the piezoelectric strips varies producing electrical energy. The output voltage of piezoelectric cantilever beam in frequency domain and time domain for acceleration of 1g i.e. 9.81m/s² and 1kohm load resistance is shown in the figure 26.

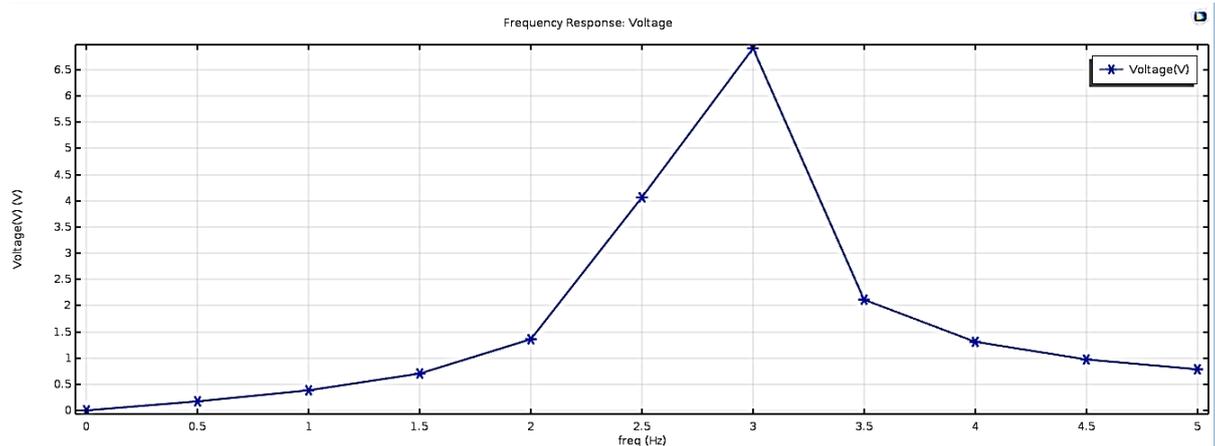


Figure 26: Frequency response voltage of piezoelectric cantilever beam

6. Conclusion

Energy consumption has risen over time, with the transport industry being a significant fuel energy consumer; thus, it must be considered while seeking environmentally sustainable solutions. This research involves the development of a system to extract vibrational energy from a vehicle suspension system, utilizing two distinct transducer technologies. The electromagnetic vibration-sensitive apparatus comprises an array of magnets and ferrofluid as a lubricant. A proof-of-concept for this device has been developed, constructed, and evaluated. An analytical model of the device has been simulated, and the output voltage has been compared with experimental results, with an examination of the reasons for inconsistencies. The device's output is influenced by the number of rotations and the selection of the permanent magnet. The output voltage generated by a neodymium N52 permanent magnet with 140 turns in the coil is 3.1V, while the current measures 0.36A.

The piezoelectric cantilever beam, the second transducer technology employed in the project, captures vibrational energy while simultaneously amplifying the frequency of vibration for the electromagnetic transducer. The combined transducers produce a rectified output voltage of 6V. The output voltage is elevated to 14V via a boost converter.

7. References

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