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Energy harvesting from road infrastructure using an innovative electromagnetic system: A Conception study

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Abstract— The growing demand for clean energy has forced the scientific community to explore the potential of energy harvesting from road infrastructures. The otherwise dissipated energy when a vehicle passes over a speed bump can be harvested and used to source traffic lights, passive sensors, traffic signals, and highway communication systems. Electromagnetic energy harvesters (EMEH) have a higher energy output than other techniques such as Piezo, pneumatic, and Hydraulics. The ongoing research on EMEH devices suffers from high energy losses, low performance, neglecting driver's comfort, and being less durable. The current study concerns improving electromagnetic energy harvesters' performance, durability, compatibility, and efficiency. A robust rectified motion EMEH machine has been designed that can transform 3mm of vertical deflection to 69mm at the output. An instantaneous power of 91 W is calculated using mathematical modeling of the system.

Keywords—Energy harvesting, Roadway infrastructures, Smart roads, Renewables

I. INTRODUCTION

The growing demand for automation and improving system performance has forced technology to investigate the prospects of harvesting green energy around us. The pursuit of clean energy has led to the exploration of energy harvesting from oceans, railways, and roads. Energy harvesting technologies include energy harvesting from photovoltaic, thermal, piezoelectric, pyroelectric, electromagnetic, and electrostatic phenomena [1]. Moreover, prospects for the use of hybrid energy harvesting systems and their potential impact in today's world are numerous [2]. Energy harvesting from roadway infrastructures aims to revolutionize the concept of smart roads [3]. Smart roads integrating traffic violation detection, fast emergence situation detection, wireless self-powered traffic signs, smart interacting roads, and electrified roads, promise to boost economic productivity, mitigate pollution, and optimize transportation. Other applications of smart roads include self-awareness, data acquisition and connectivity, self-adaptability, and energy harvesting for powering roadway accessories [4].

A. Electromagnetic energy harvesters

Electromagnetic energy harvesters (EMEH) utilize electromagnetic phenomena for energy harvesting. Electromagnetic energy harvesting is a reliable energy harvesting technique due to its superior output performance, higher power density, and longer life span as compared to other harvesting techniques. The peak power output achievable from EMEH for road applications varies from milliwatts to kilowatts. [5],[6], yet, challenges exist in energy harvesting from EMEH. Primarily, the efficiency of EMEH turns out to be sensitive to the output load conditions and the frequency of the input load. Several relevant studies highlight this behavior [7], [8]. Furthermore, EMEH suffers installation issues due to its bulkiness [9]. Efforts have been made to improve the performance of EMEH through motion rectification. Motion rectification involves transforming linear vibrations into unidirectional rotation of the generator [10]. [11] presented a similar study. An efficient mechanical motion rectifier (MMR) has been developed to convert large pulsating bidirectional oscillations into unidirectional rotation with relatively uniform velocity. Experimental results show that 10-100 W of energy can be harvested from the vibrations generated by a passing train with an efficiency of 74% at a fixed excitation frequency of 1 Hz. MMR was found to be better than non-MMR mechanisms because it reduces the effects of input force and provides smooth and even transmission of unidirectional rotary motion to the generator shaft using the flywheel.

B. Objectives

The driver's comfort is the primary concern regarding energy harvesting using a speed bump. It is recommended that the maximum allowed vertical displacement of the energy harvester is set to be 3mm. The majority of the relevant studies neglect the limit. Low output power or performance is the other problem faced during energy harvesting using a speed bump. Energy losses cause low performance during transmission. Transmission involving gears, and lead screws have adverse

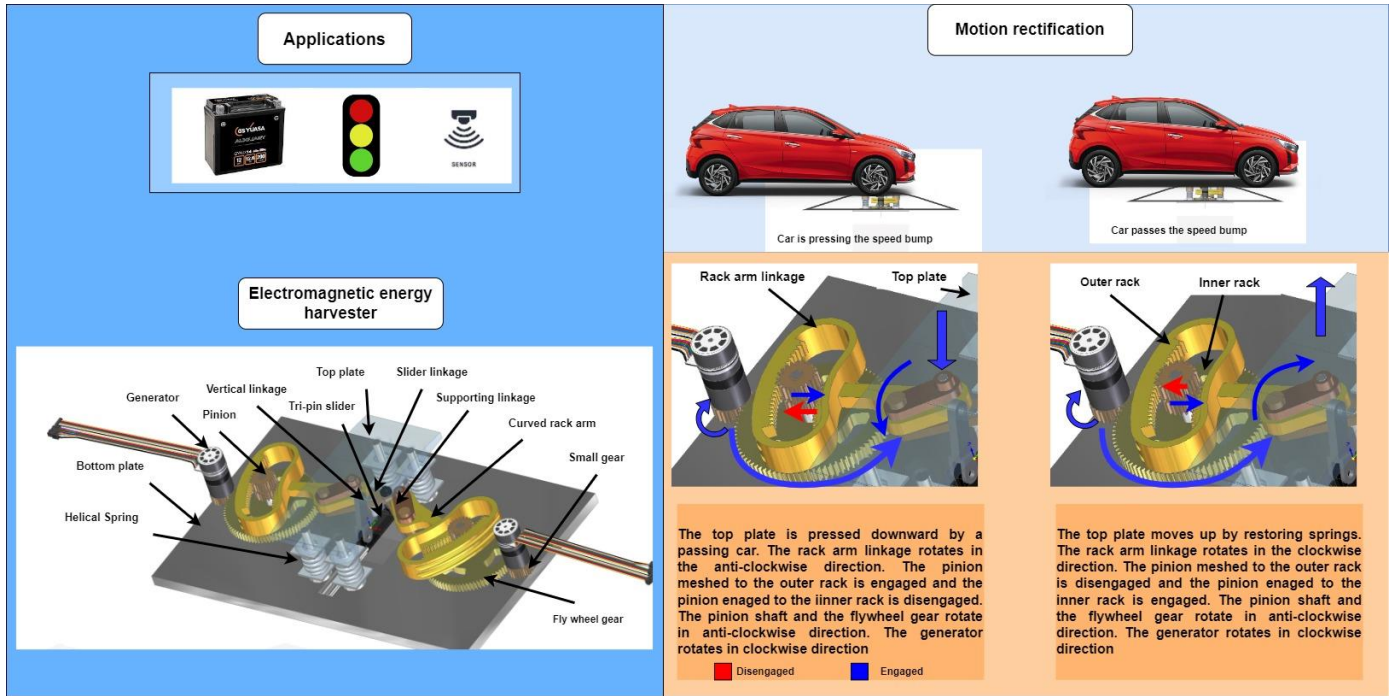


Figure. 1. Electromagnetic energy harvester developed

effects on the system's performance. Most relevant studies use gear transmission resulting in frictional losses and heaviness of the system. The study aims to replace gears with linkages to overcome transmission losses and improve the system's sensitivity to the input signal.

In summary, energy harvesting from road infrastructure finds several technical applications and can be used as a backup power resource. The project aims to replace gears with linkages to improve system performance and reduce transmission losses. Moreover, considering the driver's comfort, a vertical deflection of a maximum of 3mm is set for the speed bump. Amplifying the input signal to harvest the maximum energy possible is necessary. The current study is an effort to develop a robust, mechanically durable, deflection magnifier, efficient, and simple EMEH device that could be easily installed in a speed bump for energy harvesting.

II. SYSTEM DESIGN

The proposed prototype is shown in Fig. 1. The system consists of a top plate, a vertical linkage, a tri-pin slider, a pair of slider linkages, a pair of supporting linkages, and a pair of curved rack arms. Each curved rack arm meshes with two pinions. A shaft connects the pinion pair to a flywheel. The flywheel is linked to the generator via a small gear.

The passing vehicle presses the top plate along the z-axis. The top plate is limited to deflect in the downward direction for a maximum of 3mm. The imparted motion is transmitted to the tri-pin slider via vertical linkage. The tri-pin slider slides horizontally along the y-axis. The slider linkages connected to the tri-pin slider move due to the motion of the slider. The slider linkages in turn cause rotation in the curved rack arm linkages. The curved rack linkage consists of an external rack and an internal rack, each rack is coupled to a pinion. The pinions are

assembled on a pinion shaft which is connected to a flywheel. The pinions are assembled to the pinion shaft using one-way bearings. The one-way bearings allow motion rectification by engaging and disengaging the pinions with the pinion shaft.

The rotation in the curved rack linkage results in one of the pinions being engaged and the other disengaged. When the rotation reverses, the engagement of the pinions switches. Consequently, the pinion shaft linked to the flywheel rotates in a single direction. The flywheel smoothens the motion and transmits the motion to a generator via a small gear and the gearbox. The small gear and the gearbox amplify the rotational speed before it is fed to the generator.

A. Mathematical modeling

A rectangular coordinate system having an origin at N is used to develop a mathematical model for the EMEH (Fig. 2-a). A passing vehicle presses the top plate. The vertical linkage L_0 shown as line AB in Fig. 2-b is connected to the top plate. The vertical movement of the pressure plate is transformed into a horizontal movement of the tri-pin slider using linkage l_0 and the slider joint. Consequently, the input motion displacement is magnified, as shown in Fig. 2-b.

The physical model is simplified as a 2D drawing for clarity. In Fig. 2-a and Fig. 2-c, BO represents tri-pin slider l_s . OQ is slider linkage l_1 connected to tri-pin slider at O. QRS represents curved rack linkage. In Fig. 2-c, the distance NP is l_2 . The linear motion in the tri-pin slider causes slider linkage to slide and rotate around point $P(a, b)$ resulting $O(x_1, y_0)$ to move to $O'(x_1, y)$ shown in Fig. 2-d. The slider linkage traces an approximate circular path QQ' at the other end. The circular path is center at $R(a_2, b_2)$, where RQ represents radius l_3 . RS represents l_4 , it is the distance between R and the center of the pinion.

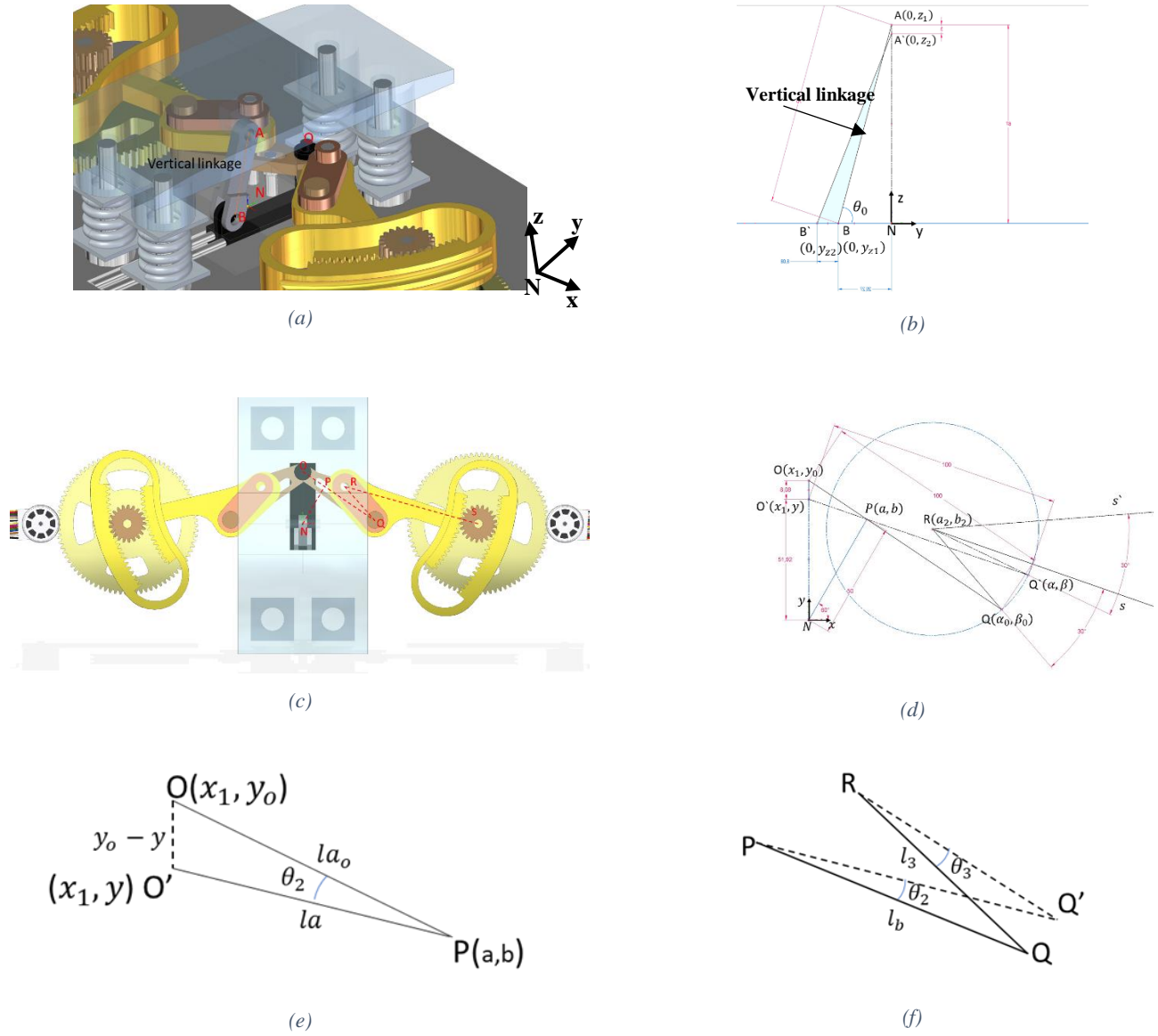


Figure 2. (a) Mathematical modeling of EMEH, (b) Kinematics in the y-z plane, (c) Top view of EMEH, (d) Kinematics in the x-y plane, (e) Kinematics of slider linkage, (f) Kinematics of curved rack arm linkage

1) Forward Kinematics

Developing the mathematical model for the EMEH involves representing linear and angular velocities of the components in terms of the vertical speed of the top plate.

θ_0 represents the angle between link l_0 and the y-axis (Fig. 2-b). θ_2 and θ_3 represent the rotation of slider linkage and curved rack linkage respectively. Where, r_p is the radius of the pinion, $\dot{\theta}_3$, $\dot{\theta}_{pin}$, $\dot{\theta}_{fw}$ and $\dot{\theta}_{gen}$ are angular velocities of the curved rack, pinion, flywheel and the generator respectively. The values represented by n_2 and n_1 correspond to the gear ratio of the flywheel-small gear assembly and the gearbox, respectively.

TABLE I. FORWARD KINEMATICS OF EMEH

Variable	Formula	Description
$\dot{\theta}_0$	$\left(\frac{(l_s - y)^2 - z^2}{l_0^2(l_s - y)}\right) \dot{z}$	Angular speed of vertical plate (Fig. 2-b)
\dot{y}	$\left(\frac{z}{l_s - y}\right) \dot{z}$	Linear speed of tri-pin slider
$\dot{\theta}_2$	$\eta_2 \left(\frac{z}{l_s - y}\right) \dot{z}$	Angular speed of Slider linkage (Fig. 2-e)
$\dot{\theta}_3$	$\eta_3 \left(\frac{z}{l_s - y}\right) \dot{z}$	Angular speed of Curved rack arm (Fig. 2-f)
$\dot{\theta}_{pin}$	$l_4 \dot{\theta}_3 / r_p$	Angular speed of the Pinion
$\dot{\theta}_{fw}$	$\dot{\theta}_{pin}$	Angular speed of flywheel
$\dot{\theta}_{gen}$	$n_2 n_1 \dot{\theta}_{pin}$	Generator rotational speed

Additionally,

$$\eta_2 = -\frac{l_a(y_o - b) + (l_{a_0} \cos \theta_2)(b - y)}{l_a^2 l_{a_0} \sin \theta_2} \quad (1)$$

$$\eta_3 = \sqrt{\left(\left(\frac{l_1 - l_a}{l_3} \right) \frac{l_a(y_o - b) + (l_{a_0} \cos \theta_2)(b - y)}{l_a^2 l_{a_0} \sin \theta_2} \right)^2 + \left(\frac{y - b}{l_a l_3} \right)^2} \quad (2)$$

2) Dynamics of EMEH

Lagrangian Mechanics aids in assessing the dynamics of the system.

$$\frac{d}{dt} \left(\frac{\partial T}{\partial \dot{z}} \right) + \frac{\partial E}{\partial z} - \frac{\partial T}{\partial z} + \frac{\partial D}{\partial \dot{z}} = f_{ext} - f_{fri} \quad (3)$$

Where, T , E and D represent the total kinetic energy of all moving components of the system, total potential energy stored by the components of the system, and damping energy of the system respectively. f_{ext} and f_{fri} are the external forces and the frictional forces respectively.

$$T = \frac{1}{2} m_{plate} (\dot{z})^2 + \frac{1}{2} J_{L_0} (\dot{\theta}_0)^2 + \frac{1}{2} m_{L_5} (\dot{y})^2 + 2 \left(\frac{1}{2} m_{L_1} (\dot{l}_a)^2 + \frac{1}{2} J_{L_1} (\dot{\theta}_2)^2 + \frac{1}{2} J_{L_3 L_4} (\dot{\theta}_3)^2 + \frac{1}{2} (J_{bearing} + J_{shaft} + J_{fw}) (\dot{\theta}_{pin})^2 + \frac{1}{2} (J_{gearbox} + J_{sg}) (n_1 \dot{\theta}_{pin})^2 + \frac{1}{2} J_{generator} (\dot{\theta}_{gen})^2 \right) \quad (4)$$

$$E = \sum_{n=1}^m (Potential\ energy)_n = 4 \left(\frac{1}{2} k(z - z_o)^2 \right) \quad (5)$$

m_{plate} , m_{L_5} , m_{L_1} , J_{L_1} , $J_{L_3 L_4}$, $J_{bearing}$, J_{shaft} , J_{fw} , $J_{gearbox}$, J_{sg} , $J_{generator}$ and k represent mass of the top plate, mass of tri-pin slider, mass of the slider linkage, inertia of the slider linkage around P, inertia of curved rack linkage around R, inertia of the bearing, inertia of the pinion shaft, inertia of the gearbox, inertia of flywheel, inertia of small gear, inertia of the generator and the spring constant respectively. z_o is the equilibrium position of the top plate.

The coupling of two electric generators to the energy harvesters induces electric damping given in eq (6).

$$D = \left(C_w + \frac{1.5 k_e^2 (n_2 n_1)^2}{(R_i + R_e) \eta_r \eta_g} \right) \left(\frac{l_4}{r_p} \right)^2 \eta_3^2 \left(\frac{z}{l_s - y} \right)^2 (\dot{z})^2 \quad (6)$$

Where, k_e , R_i , R_e , C_w , η_g and η_r are back electromotive voltage constant of the generator, generator internal load, generator external load, damping coefficient of the gearbox, mechanical efficiency of the generator and the mechanical efficiency of the curved rack arm respectively. Applying (4),(5),(6) in (3), a nonlinear differential equation is obtained.

$$(I_1 \ddot{z} + I_2 (\dot{z})^2) + 4k(z - z_o) + I_3 \dot{z} = f_{ext} - f_{fri} \quad (7)$$

Where, I_1 , I_2 and I_3 depend on z , \dot{z} , η_2 , η_3 , r_p , l_o , l_1 , l_2 , l_3 and l_4 . \ddot{z} is 2nd derivative of z with respect to time.

3) Electric circuit of the system

A three-phase brushless DC motor coupled with a gearbox is used for the simulation studies of the system. The electromotive voltage constant of the generator is k_e . In addition, the gear ratio of the gearbox is n_1 . The three-phase brushless generator distributes its instantaneous power across three identical resistors (denoted as R_{ext}) as shown in Fig. 3.

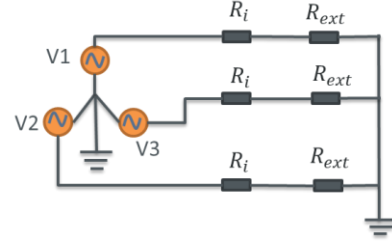


Figure. 3. Electric circuit of EMEH

III. RESULTS AND DISCUSSION

The non-linear differential equation (7) is solved using the finite element method (FEM) in an open-source platform. Results obtained by solving the differential equations help estimate the efficiency, and power output of the system. The parameters and their values are listed in Table 2. The values are chosen based on dimensional constraints, material considered, and literature studies.

A. Efficiency and power estimation

The work done by a vehicle passing over the speed bump can be estimated as:

$$W_{mec} = \int_0^z f_{ext}(t) dz \quad (8)$$

The brushless DC generator of three windings converts the mechanical energy to electrical energy. Considering each winding has the same internal resistance R_i , and is subjected to the same external resistance R_e . The output electrical energy can be estimated for two generators of the system as:

$$dW_{ele} = 2P_{ins} dt$$

$$W_{ele} = 2 \int_0^t P_{ins}(t) dt \quad (9)$$

Where, $P_{ins} = 1.5 \frac{V^2}{R_e}$, is the instantaneous power of the generator across three resistors each R_e , and $V = \frac{R_e}{R_e + R_i} k_e \dot{\theta}_{gen}$.

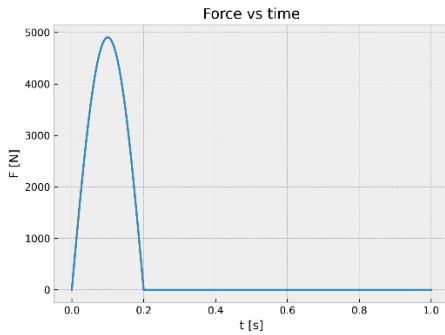
The efficiency of the system can be written as:

$$\eta_{sys} = \frac{W_{ele}}{W_{mec}} \quad (10)$$

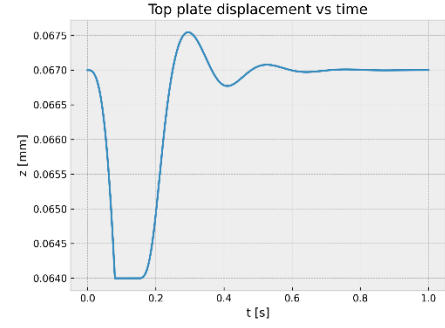
Estimating the power output of the system is essential to determine the potential applications of the system. Considering a vehicle of mass 2000kg with a wheelbase value of 2.5m passes over the EMEH with a speed of 0.5 m/s.

TABLE II. PARAMETERS FOR SIMULATION STUDIES

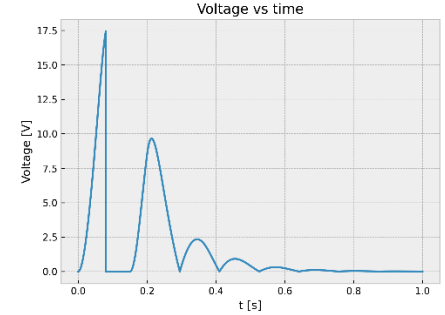
Parameter	Description	Val
L_0 [mm]	Vertical linkage	70
L_s [mm]	Tri-pin slider	80.273
L_1 [mm]	Slider linkage length	100
L_2 [mm]	Distance NP in (Fig. 2-d)	55
L_3 [mm]	Distance QR in (Fig. 2-d)	45.75
L_4 [mm]	Distance RS in (Fig. 2-d)	180
y_0 [mm]	Initial distance ON in (Fig. 2-d)	67
θ_1 [deg]	The angle between OP and the x-axis	60
m_{plate} [kg]	Mass of the top plate	2
m_{L_s} [kg]	Mass of the tri-pin slider	.05
m_{L_1} [kg]	Mass of the slider linkage	0.7
J_{L_1} [kgmm ²]	The rotational inertia of slider linkage	2
$J_{L_3L_4}$ [kgmm ²]	The rotational inertia of curved rack linkage	50
$J_{bearing}$ [kgmm ²]	Pinion and one-way bearing assembly rotation inertia	10
J_{shaft} [kgmm ²]	The rotational inertia of the pinion shaft	5
J_{fw} [kgmm ²]	The rotational inertia of the flywheel	20
J_{sg} [kgmm ²]	Rotational inertia of small gear	5
$J_{gearbox}$ [kgmm ²]	The rotational inertia of the gearbox	10
$J_{generatr}$ [kgmm ²]	The rotational inertia of the generator	25
n_1	Gear ratio small gear and flywheel	2
n_2	The gear ratio of the gearbox	3.7
k [kN/m]	Spring constant	300
k_e [Vs/rad]	Generator constant	0.0458
R_i [Ω]	Internal resistance of the generator	1.25
R_e [Ω]	External resistance of the circuit	10
r_p [mm]	Pinion radius	40
r_b [mm]	Bearing radius	5
C_w [V ² s ² / Ω rad ²]	The damping coefficient of the gearbox	0.05
η_g	Efficiency of the generator	0.90
η_r	Efficiency of the curved rack	0.95



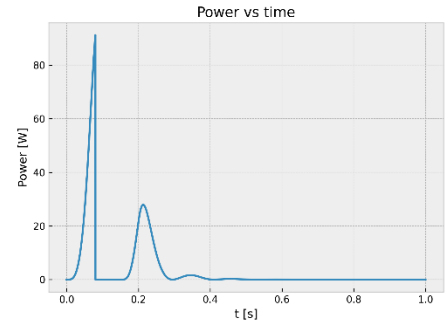
(a)



(b)



(c)



(d)

Figure 4. (a) Force exerted by a moving vehicle on EMEH vs time, (b) Top plate vertical displacement vs time, (c) Output voltage of EMEH vs time, (d) Power output of EMEH vs time

Considering a sinusoidal force exerted by the tire of the passing vehicle on the top plate shown in Fig. 4-a. The consequent vertical displacement in the top plate is shown in Fig. 4-b. The top plate undergoes a vertical downward shift of 3mm caused by the applied force. After the car tire moves beyond the top plate, the helical springs restore it to its original position. Subsequently, the upper plate oscillates around its initial location before returning to its original state. The EMEH harvests an energy of 3.65J for an input energy of 12.33J with an average efficiency of 30%. The simulation reveals a peak instantaneous voltage of 17.5V shown in Fig. 4-c. Two peaks in Fig. 4-d represent energy harvesting for both the downward and upward motion of the top plate. The energy stored in the helical springs is utilized to harvest energy during the upward motion of the top plate. A peak instantaneous power of around

91W points to the large force exerted by the vehicle on the system.

IV. CONCLUSION

The paper presented an innovative electromagnetic energy harvester for road infrastructures. The EMEH device efficiently amplifies vertical displacement from vehicles, utilizing an innovative mechanical mechanism that significantly enhances input displacement before transmitting it to an electric motor. The bi-directional vertical displacement of the top plate is converted to uni-directional rotation of the generator shaft. Moreover, the use of linkages instead of traditional gear mechanisms minimizes mechanical losses and ensures a compact design with higher power density. Furthermore, it enhances the mechanical durability of the system.

A mathematical model based on Lagrange mechanics is presented for the system. The model considers both frictional losses and electric damping losses. The simulation results show that for a vehicle of mass, 2000kg with a wheelbase value of 2.5m passes over the EMEH with a speed of 0.5 m/s, the EMEH harvests an energy of 3.65J for an input energy of 12.33J. An average efficiency of 30% is calculated for the system. A peak power of 91W and a peak voltage of 17.5V is calculated for the system.

Looking ahead, the fabrication of the prototype will provide invaluable insights into the system performance and validation of the mathematical modeling. It would help optimize the performance of the system paving the way for further research and innovation.

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