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Mathematical Modeling Of Regenerative Electromagnetic Suspension System

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Abstract: This research aims to design and fabricate a linear regenerative electromagnetic shock absorber for Electric Vehicles. This mechanism will act as a continuous source of electric energy to deliver power to a vehicle's electronic component. Different arrangements of cylindrical magnets and coil arrangements with various sizes will be considered under review and analysis. An efficient design of linear regenerative electromagnetic shock absorbers will be modeled by using the computer-aided design software program (SolidWorks®) and a simulation will be executed. A design of suitable power electronics will be proposed to convert and store the generated electrical energy.

***Index Terms* - Regenerative, Suspension system, automobile, damping, stiffness etc.**

1.INTRODUCTION

An automobile's suspension system acts as a connection between the wheel and the vehicle's body. It allows relative motion between them and absorbs road shocks and vibrations and prevents the vibration from reaching the passengers. Due to the suspension system comfortable ride and contact between tire and road surface is ensured which in turn provides good handling , road performance and safe drive. A passenger vehicle cannot be imagined without a suspension system. Suspension absorbs a lot of engine energy as heat in damper and spring .this happens due to the damper friction and deformation of the spring coil . If there can be way for the extraction of lost energy and converting it into electrical energy it will make a great sense . Every disturbance will be converted into full energy, which can be supplied to vehicles electronic system or added to charge the batteries.

The suspension system of a vehicle functions as a mechanical system that supports the sprung and interacts with the un-sprung masses of a vehicle. The sprung mass is the vehicle body and the un-sprung mass is the wheel. It isolates the vehicle body from road disturbances and helps the wheel to hold onto various road surfaces. There are bumpy roads, acceleration or reduction of the driving speed, and the operations of the steering wheel when driving a vehicle [4]. This behavior causes relative shock between the sprung mass and un-sprung mass. The shock is a part of mechanical power that can be recycled [5]. The suspension system provides better road handling for passenger comfort [3, 6]. The main element in the suspension system is the damper and spring. The damper is the one that absorbs the vibration produced by the road irregularities and dissipates the energy to the surrounding. This energy can be harvested with a modification of the suspension system called the energy regenerative suspension system [3]. The research about vibration harvesting on suspension was started about two decades ago. It was an approach to improve the fuel consumption of land vehicles [7]. Regeneration of waste energy is one of the important elements in mechanical engineering fields [8]. There are several studies and research on the regenerative suspension system and improvement on the designed system but until now the development is still far away from the demands of commercial applications. There are only some researchers that discovered and made a concrete achievement in a specific test. The magnets can be arranged to provide longitudinal or transverse magnetic flux [6,12]. A 13.5 % reduction in car body acceleration was observed, increasing the ride comfortability [3]. We used the rack and pinion system was able to generate 12 watts of power from all wheels of the car [2]. We conducted [1] in which we get maximum output power of 0.58 Watt was calculated.

2. Problem Statement

The suspension system is to be designed can by using faraday's law of electromagnetic induction, which can harvest or regenerate the energy lost in the suspension system damper and spring as heat energy. When an extensive literature review was done it was found that a lot of work has already been done in this area and there are a lot of scopes to increase the efficiency of the system the work done is in the preliminary stage. Also in many research papers, it was found that not all the aspects of the research and design are taken into account as a whole like in the paper the vehicle mass was not considered, and also the value of a magnetic constant was estimated from the experiment itself. The literature review was done from various resources such as research papers, TV, the Internet, journals, and articles. It was found that extensive research is undergoing in this field. Researchers and scientists all over the world are keen to develop this system with greater efficiency high-reliability low cost and maintenance and with more modularity. The differential equation governing the quarter car suspension model was analyzed also various laws of physics which are given in the methodology section are studied and revised. A research paper [1] was reviewed and its data and works were studied in depth it was found that in that research paper, there were some shortcomings, and also the magnetic field constant and coupling coefficient values we are determined experimentally from the simulation results. Accordingly, a new design will be proposed and a mathematical equation governing the design will be formulated.

3. Objective

The objective of this research paper is to design and develop a linear regenerative electromagnetic shock absorber for an electric vehicle suspension system. As rising fuel cost and pollution has become a major concern in the 21st century it has become mandatory and it has become a compulsion to think about alternative source of energy for human being and the survival of the human race. The internal combustion engine is the most revolutionary machine ever created by a human being. During World War 2 it was the most used machine in this world. From land vehicles to aircraft all were powered by IC engines. But as the population of this world increased at an alarming rate more and more consumption of fossil fuel is happening this had led to a great problem in this world the greenhouse effect and global warming. To solve this issue lot of discussions and summits are happening all over the world like the Geneva Convention. A lot of steps have already been taken and one among those is to transition from conventional IC engines to electric vehicles. To adopt electric vehicles in India the Government of India is doing a lot of effort and it has recently launched its new electric vehicle policy and Fame II (Faster adoption and manufacturing of electric vehicle) policy in India. As a result, a lot of Indian companies are already launching their electric vehicles like Tata and Mahindra, and the very famous Tesla company also known as the pioneer in this industry. It is well-known fact in mechanical /automobile engineering that about 60% of the total power output by the engine is dissipated in the suspension system as heat. If this loss of energy can be utilized and can be converted to the electrical energy it can be used to charge the battery or can be used to power up internal accessories. Whatever way it may be used, it will increase the efficiency and range of the vehicle as energy lost in the suspension will be generated and reutilized add this is from the second law of thermodynamics that 'energy *can neither be created nor destroyed.'*

4. **Methodology**

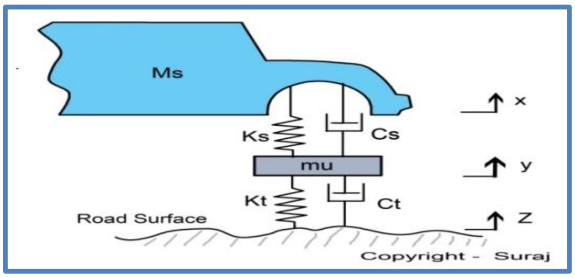


Figure 1. A design of a quarter-car suspension model

Table 1 Different Types of symbols and it's description

Symbol	Description
Ms	Car Body Mass
Mu	Suspension mass
Ks	Suspension Coil Spring Constant
Kt	Tyre Spring Constant
Cs	Suspension Damper Constant
Ct	Tyre Damping Constant
x	Car Body Displacement
Y	Suspension Displacement
z	Road irregularities

The following laws of physics are used :-

Newton's second law of motion – *" Force is equal to the rate of change of momentum"*

$$\boldsymbol{F = \frac{dp}{dt}}$$

Faraday's law of electromagnetic induction

1st law – There is emf

2nd law – How much emf

Lenz law – Direction of emf

Faraday's law of electromagnetic induction "The induced emf in the circuit is equal to the rate of change of flux linkage . "

Kirchhoff's Voltage Law :- The voltage around a loop equals the sum of every voltage drop in the same loops for any closed network and equals zero.

Lenz law : " The direction of the current induced in a conductor by a changing magnetic field is such that it opposes the initial changing magnetic field which produced it ."

Right Hand thumb rule : " The emf generated in any coil is such that it opposes the change in magnetic flux which tends to generate that emf . "

$$\boldsymbol{\varepsilon} = -\frac{d\boldsymbol{\Phi}}{dt}$$

The negative sign indicates the induced EMF acts to oppose the change. If a coil consists of N loops with the same area, the total induced EMF in the coil is given by

$$\boldsymbol{\varepsilon} = -N\frac{d\boldsymbol{\Phi}}{dt}$$

EMF can be induced in several ways,

- The magnitude of B can change with time
- The area enclosed by the loop can change with time.
- The angle between B and the normal to the loop can change with time.
- Any Combination of above can occur.

4.1 Design

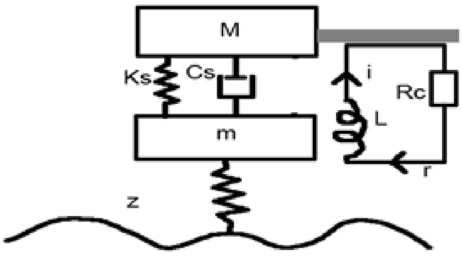


Figure 2 Quarter Car suspension model used in this project

Table 2 Different types of Symbols used in Fig 2

Symbol	Description
Ks	Spring Constant
Kt	Tyre Spring Constant
Cs	Damping Coefficient of Damper
Bs	Damping Coefficient to magnetic force
M	Sprung mass (Car)
M	Un-sprung mass (Magnet)
X	car position
Y	Magnet position
Z	Road disturbances
r_c	Resistance of coil
R_l	Load resistance

4.1.1Prototype Specifications

1.Suspension Type – MacPherson strut

2..Winding Coil Design -

12 SWG Copper wire is used
Coil Outer Diameter(D) - 92mm
Coil Inner Diameter - 76mm
Coil Length -100mm
Coil Depth -8mm

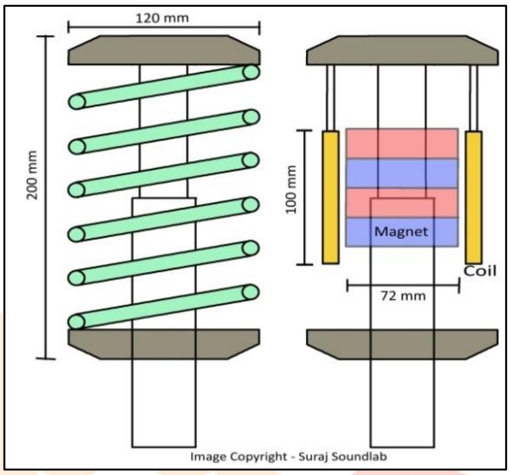
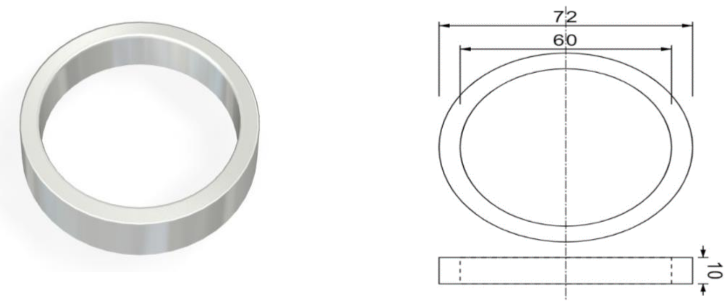


Figure 3 . Diagram of the prototype

Figure 4 . Ford Aspire Car

Table2 . Magnet Specifications

Magnet	Material Grade	N Neodymium 45
Shape	Type	Ring
	Diameter	OD - 72mm
	Inner Diameter	ID - 60mm
	Height	10mm
	Direction	Radially
	Number Used	10 Units
Operating Environment	Gap	0 mm
	Temperature	50 °C
	yoke	None
Magnetic Characteristics Measuring Point (P)	Surface Flux Density	B -27.98 mT
	Attractive force	F -- kgf
	Magnetic Flux Density on load point	Bd 770.89 mT
	Total Flux	ϕo 0.0009594 Wb
	Permeance Coefficient	Pc 1.91
	Net Weight	93.31 g
Material Characteristics	Remanence	Br 1195 mT
	Coercive Forces	Hcb ≥ 10.9 kOe
	Intrinsic Coercivity	Hcj ≥ 12 kOe
	Maximum Energy Product	BH 33-36
	Temperature Coefficient	Br -0.12 %/°C
		Hcj -0.55 %/°C
	Max. Operating Temperature	Tw ≤ 80 °C
	Curie Temperature	Tc 310
	Density	ρ 7.5 kg/m3



(a)

(b)

Figure 5.(a) Ring Magnet (b) Dimension of ring magnet

The data given in the above table no. was calculated from the online software of the MAGFINE Company site [9] the magnetic flux density
B = 0.03 T
Since 10 magnets are used therefore
Total flux = 10 × 0.03 = 0.3 T
Net weight of the magnet = 10 × 93.31 g
= 933.1 g or 0.933 kilogram
There is an air gap of 2 mm between the magnet and the coil. The magnet is attached with strut tube and the coil is attached with the strut top mounting as shown in fig.

4.2 Mathematical Modelling

4.2.1 Free body diagram for Sprung mass

$$m\frac{d^2x}{dt^2} + kx + c\frac{dx}{dt} - ky - c\frac{dy}{dt} - NBli = 0 \quad .(1)$$

From Kirchhoff's law,

$$L\frac{di}{dt} + iR + NBL\frac{dx}{dt} = 0 \ldots\ldots\ldots\ldots\ldots\ldots(II)$$

R = Net Resistance = $r_c + R_l$

The deformation in tire is neglected for mathematical simplicity. As a result road irregularities equals the magnet movement which is denoted by 'y' in the Table 2.

4.2.2 Spring Stiffness calculation

The car used for reference in this experiment is *Ford Aspire 2019 model – 1.2L TIVCT (5 Speed Manual Transmission)* whose gross weight is 1,460 Kg .figure 4 [*Source – Ford Owner's Manual]*
The force required to extend or compress a spring can be expressed with help of Hooke's law.
F=-k × s where,
F= force (N)
k= spring constant (N/m)
s=extension or compression distance
The maximum allowed compression is 0.1 m
Load on each wheel =1460/4 =365 kg
The force acting on each spring can be calculated using Newton's second law
F = 365 × 9.81 = 3580.65 N
Multiplying it with 1.5 times for handling dynamic forces, potholes etc.
3580.65 ×1.5 = 5370.975 N , Or say , 5370 N
The required spring constant for the suspension
K=-F/s
= -(5370 N)/(-0.1m)
= 53700 N/m
= 53.7 kN/m

4.2.3 Inductance *:*

It is calculated from the formula

$$L = \frac{N^2 \times D^2}{18D + 40l}$$

Where ,
L= Inductance
N = No. of turns
D = Mean Diameter of coil
l=length of coil
L = 5177.04 μH

4.2.4. Damping

The typical value for the damping ratio for a passenger car Barry from 0.2 - 0.4 for a comfortable ride. In racing car this may reach to 0.6 - 0.7 to prevent the loss of energy in damping. 1 denotes the 100% or critical damping. Critical damping means the oscillation stops as soon as possible after the oscillator passes through the mean position.
The magnetic coupling between the mechanical port and electrical port will act as a resistance to the motion and hence will act as a damper.
Damping ratio , $\zeta = \frac{c}{2\sqrt{mk}}$
Taking $\zeta = 0.32$ for a safe comfortable ride,
We get C = 2833.43 , or 28344
Both the damper are in parallel therefore
$C = C_1 + C_2$
C_1 = Damping ue to mechanical Damper
C_2 = Damping due to magnetic coupling
Also the magnetic damping equals to –

$$C_2 = \frac{(NBL)^2}{R}$$

Due to unavailability of Tesla meter the value of magnetic flux is calculated from the online software already mentioned in design section of this paper[9].

4.2.5 Wire Resistance Calculation

Internal resistance of the Coil wire is calculated as,
Number of turns (N) =

$$N = \frac{Coil\ Length}{Wire\ Dia} \times \frac{Coil\ Depth}{Wire\ Dia}$$

Length of wire = N × π × Coil mean Dia.
For **SWG 14** Wire
Max Current Rating = 6.49 A
Wire Diameter = 2.03 mm
R = 0.00532 Ω/m

$$N = \frac{Coil\ Length}{Wire\ Dia} \times \frac{Coil\ Depth}{Wire\ Dia}$$

N = 194
Length of wire = 194 *3.14 *84 =51.195 m
R = 51.195 * 0.0053 = 0.27Ω

4.2.6 Load Resistance Calculation

Resistance of car Stereo system
Assuming a stereo system 'KDC 264 UCB' from Kenwood Company[10]
Details of Audio System is
Power = 50 ×4 =200 W
Operating Voltage = 10.5 V -16 V
Max Current Consumption = 10A
Assuming the working range V = 12 V and
I = 10A
$R_l = V/I$, = 12/10 = 1.2 Ω
Both are in series
Now total Resistance of the system =
$r_c + R_l = 0.27 + 1.2 = 1.47\Omega$
Considering Connecting wires and power electronics =1.5 Ω

5.Result And Discussion

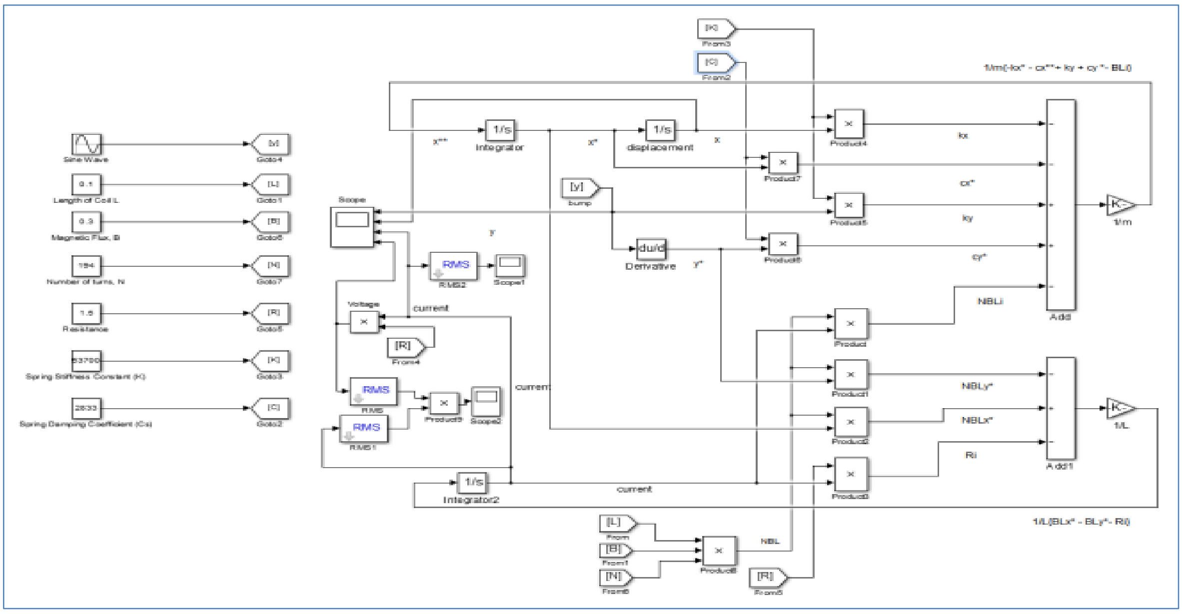


Figure 6. Simulink Model

The Simulink model shown in fig have a provision for nine different parameters as input listed below

1. Road bump as a sine wave having the amplitude of 0.05 m and frequency of 5 Hz or 31.4 rad/s
2. Length of the coil ‘L’ = 0.1m
3. Magnetic flux ‘B’ = 0.3 T
4. Number of turns ‘N’= 194
5. Total Resistance ‘R’= 1.5 Ω
6. Spring Stiffness Constant ‘k’ =53700 N/m
7. Damping Coefficient ‘C’ =2833 kg/s
8. Sprung Mass ‘M’= 364 kg
9. Inductance if coil ‘L’ =5.17$e^{-0.3}$ Henry

The experiment was run for time ‘t’ = 1 s and corresponding output graph is shown below in figure 7.

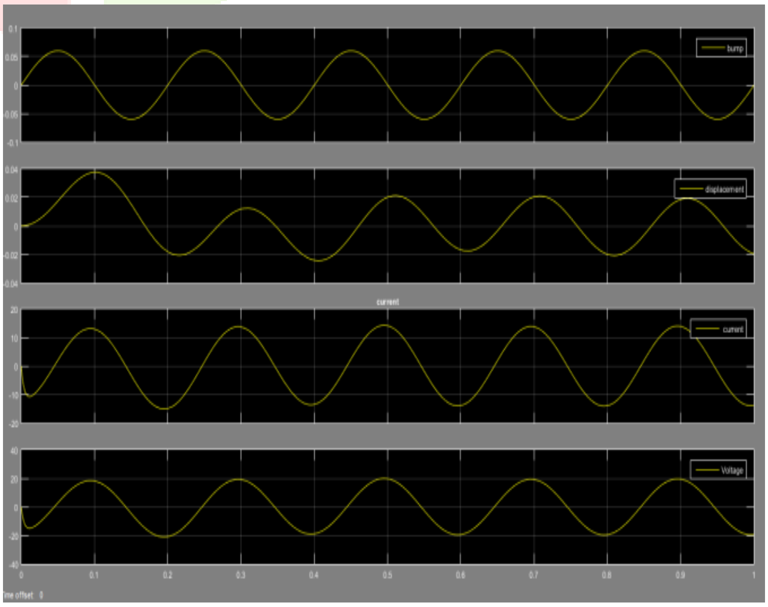
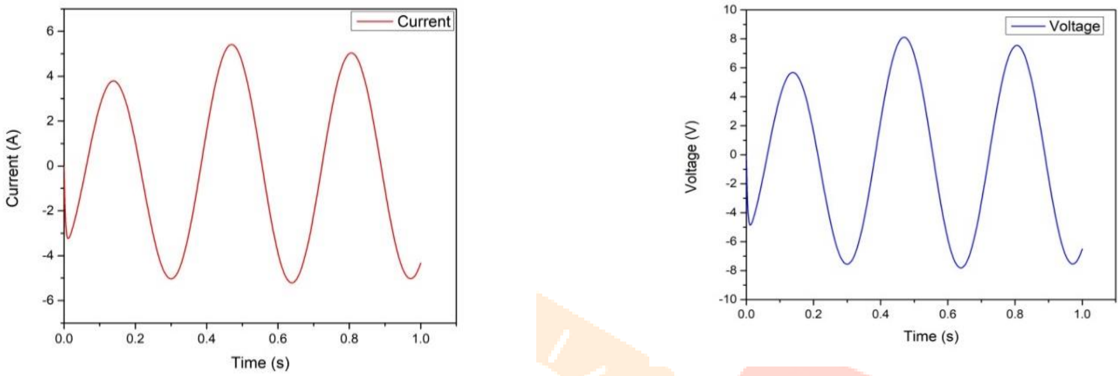


Figure 7. Simulink Graph

Since input was a sinewave Both the Voltage and Current waveforms obtained were pure sinewave . In the above figure time is denoted in x axis in all the four plots . First plot shows road disturbance vs time . 2nd plot shows the vertical displacement of car vs time . 3rd shoes the generated current and 4th one shows the output voltage.

5.1 Output Voltage and Current

While operating in the above given condition of frequency and amplitude of the disturbance 5.4 A of maximum current and 8.11 V of maximum voltage was generated.



(a)

(b)

Figure 8 (a) current vs time (b) voltage vs time

Figure 8 and 9 shows the output current and voltage respectively with time.
Imax =5.4
Irms =5.4/$\sqrt{2}$ = 3.81 A
Vmax = 8.11
Vrms = 8.11/$\sqrt{2}$ = 5.73V
Power = Irms × Vrms = 3.81× 5.73= 21.83 watt
If multiplied by 4 for all wheels of car
21.83 × 4 = 87.32 watt
This amounts to the expected result from this experiment.

5.2Analysis of output power for various frequencies

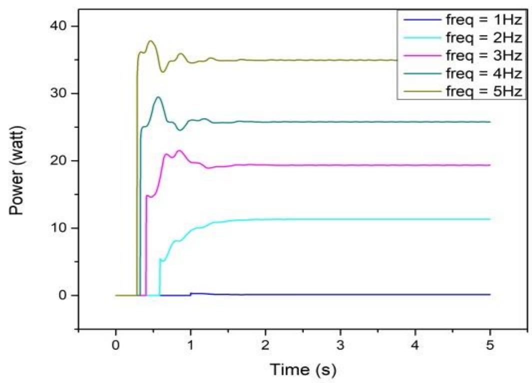


Figure 9. Power at various frequencies

Figure 9 is a plot between current and time which shows the output power for set of five frequency for time 5 s taking values ranging from 1 Hz to 5Hz. There is variation in Initial power developed but after 1.5 s power curve is smooth . Power curve is obtained from the formula P = Irms × Vrms . It was found that increasing the frequency of the disturbance the output power increases but in real road conditions frequency will be limited to 1-3 Hz.

5.3 Input Disturbance and its effect on output current

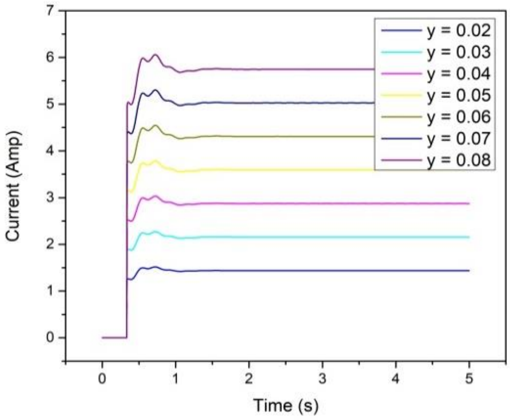


Figure10. Current with different road bump

Figure 10 shows variation of current with time when Road disturbance y is increased from 0.02 m to 0.08 m in steps of 0.01m keeping the frequency constant at 3 Hz. Increasing the road bump increases the current. This happens due to the fact that induced emf is rate of chance of flux. Increasing disturbance will increase the rate of flux change because frequency is fixed.

5.4 Spring stiffness Analysis

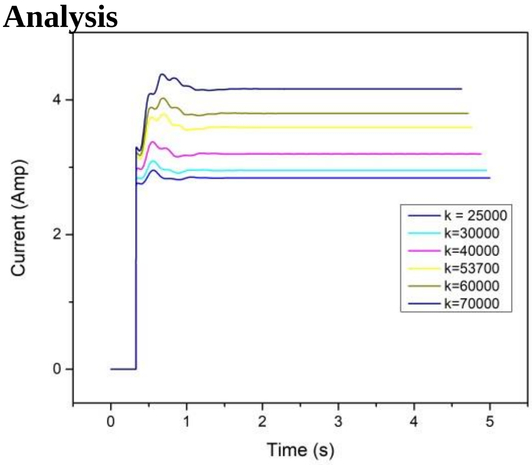


Figure 11. Current with different spring stiffness

Figure 11 shows variation of current with time when the value of spring stiffness constant changes. Increasing the spring stiffness constant from 25000 N/m to 70000 N/m increases the current from 2.8 A to 4.2 A, but there is a decrease in Damping ratio from 0.46 to 0.28. Thus, increase in current will compromise on the riding comfort.

6. Conclusion

The aim of this research to achieve commercially acceptable power rating was completed in this experiment. A prototype is made and simulation result shows that combined energy 87.32-watt power regeneration is possible from all the four-suspension system of the chosen vehicle. First the dimensions of the original suspension were measured and accordingly a prototype was designed. Suitable copper wire is chosen from the SWG chart. Total length resistance, inductance of the wire and the coil is calculated. The design of magnet is done and the value of magnetic flux was obtained using the online software. A mathematical model representing the free body diagram and Kirchhoff's voltage law was presented and accordingly Simulink model was prepared. A test was done to obtain current and voltage and after that various analysis was done for different values of road bump input frequency and spring constant.

Conflicts of Interest

The authors declare no conflict of interest.

Author Contributions

The background work of the paper, literature review, methodology, dataset collection, implementation, result analysis and comparison, preparing and editing draft, visualization have been done by first, second and third author . The supervision, review of work and project administration, have been done by fourth author.

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