DESIGN OF A NOVEL REGENERATIVE SHOCK ABSORBER

Shrijeet Nagori[1]

[1]*Student, Btech (Mechanical Engineering), Maharashtra Institute of Technology-World Peace University (MIT-WPU), Kothrud, Pune 411038*

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Abstract -Nowadays EV technology is booming and there are numerous automobile giants along with new startups that are developing technologies for solving the problem of fast charging in EV's as well as consuming power in an efficient way by minimizing the power losses by using regenerative technologies. This paper proposes one such novel design of generating electricity with the help of shock absorber while the automobile is in operation and storing it in a capacitor and utilizing it later. Vibration occurs between the road surface and car body when driving on irregular road surface. The function of regenerative shock absorbers is to recover this vibration energy, which can be dissipated in the form of heat as waste. The proposed design has incorporated a monotube shock absorber integrated with a generating module which works on faradays law of electromagnetism. The generating module consist of an array of NdFeB magnets which will be reciprocating in copper windings thus generating electricity.

***Key Words*:**Monotube shock absorber, Magnetic array, Faraday's law of electromagnetism, Regenerative technology, vibration, energy, heat, vehicle suspension system.

1.INTRODUCTION

According to studies only 10 to 16 percent of the available fuel energy is used to drive the vehicle, the remaining energy is dissipated in the form of heat. One such form of energy loss is due to undesirable vibrations. A shock absorber is used for dampening these vibrations to ensure rider comfort and safety and maintain optimum wheel contact. In a conventional shock absorber, the kinetic energy of vibration is converted in heat energy via damping effect. Through the use of generating module, the regenerative shock absorber will convert this kinetic energy into electrical energy rather than heat. The generating module comprises of a permanent magnet stack embedded into the main piston, stator winding coils, a rectifier and an Electronic control unit to dampen and manage the dynamic loads. The magnet stack will reciprocate within the annular array of stator windings which will generate an alternating current due to faraday's law of electromagnetism. The electricity generated will be converted to DC current using a full wave rectifier and will be stored in vehicle battery for further use.

2. CONVENTIONAL SHOCK ABSORBER

A Shock absorber is basically an oil pump placed between the frame of the car and the wheels. The upper mount of the shock absorber connects to the frame (i.e., the sprung weight), while the lower mount connects to the axle, near the wheel (i.e., the unsprung weight). It is a device which is designed to dampen shock impulses and dissipate kinetic energy into heat in presence of a viscous fluid. The shock absorbers help in reduction of rate of bounce, maintains optimum wheel contact and prevents vehicle body roll and pitch and ensures rider safety.

Shock absorbers work in two cycles — the compression cycle and the extension cycle. The compression cycle occurs as the piston moves downward, compressing the hydraulic fluid in the chamber below the piston. The extension cycle occurs as the piston moves toward the top of the pressure tube, compressing the fluid in the chamber above the piston.

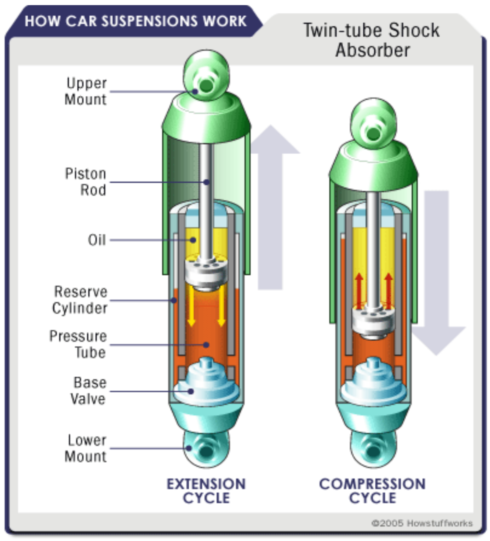


Fig -1: Working of Shock Absorber (Image courtesy: howstuffworks.com)

There are mainly three types of shock absorbers:

1. **Air Shock Absorber** which consist of an air chamber, iron piston and a fluid.
2. **Monotube shock absorbers** which consist of a single tube with two valves which open subsequently in compression and expansion stroke's. The speed and nature of bump decides the amount of fluid being passed through valves. For low speed small bumps, a large quantity of fluid is passed as larger valves open and for high speed strong bumps small amount of fluid is passed.
3. **Dual Tube shock absorbers** which consist of coaxial concentric cylindrical tubes. The inner tube is called as pressure tube and the outer tube is

called as reserve tube. A base valve is located at the bottom of inner tube. Due to bumps, there is reciprocation of piston which leads to movement of fluid between different chambers through valves and hence conversion of kinetic energy into heat is achieved.

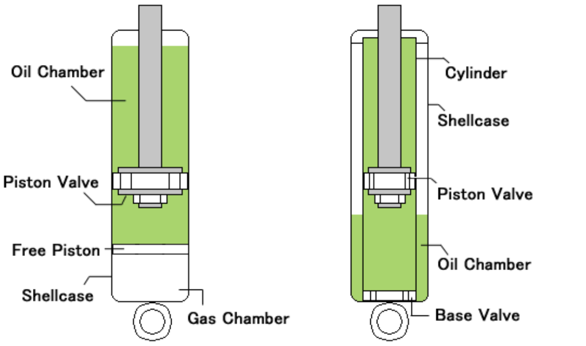


Fig-2: Monotube and Twin tube shock absorber (Image courtesy: www.tein.co.jp)

Advantages of mono tube damper over twin tube damper:

● Very wide damping rates can be achieved through bigger diameter pistons and shims designs.

● Plush feel and full control over all piston speeds through higher damping rates.

● Cools faster and more reliable then the single precision tube shock body.

● Bigger diameter piston rods can be used because of bigger internal chambers with sufficient oil.

● Can withstand higher pressures and temperatures without aeration or foaming.

3. LITERATURE SURVEY

The purpose of this literature review is concerned with study of monotube shock absorbers in bikes, their dimensions, design of monotube shock absorbers, existing papers for regenerative shock absorbers with theoretical and experimental evaluation.

[1] Study of Yamaha FZ suspension system was done to know the overall dimensions of a conventional shock absorber. Researches to recover vibration energy have been going on for decades. Regenerative shock absorber designs can be mainly classified in three main categories namely linear design [2], bidirectional rotary design[3] and unidirectional rotary design[4]. In the first category, linear electromagnetic regenerative shock absorbers utilizing coils of magnetic wire are used to generate electricity directly. The efficiency of this method is typically very high, but its damping coefficient is small relatively. In [5], Zhang et al. designed an electromagnetic shock absorber utilizing a rack and pinion mechanism. The damping coefficient of the shock absorber was only 30 N·s/m, which is far below the standard value. In [6], Tang et al. proposed a linear vibration energy harvester with an efficiency of 70–78%. However, the maximum damping coefficient was only 940 N·s/m under short circuit conditions. The second category is bidirectional rotatory regenerative shock absorbers, which are designed to increase damping coefficients. By utilizing mechanical structures, such as a rack and pinion [7], ball screws [8], or novel structures [9], irregularly reciprocating linear oscillations are transformed into two-way high-speed rotation. The third category is unidirectional rotary regenerative shock absorbers, which transform irregularly reciprocating linear vibrations into unidirectional rotation. Therefore, this type of generator always rotates in one direction, which increases the efficiency of the energy-harvesting system and decreases the backlash between transmission structures compared to the second category. In [10], based on helical gears and dual tapered roller clutches, Salman et al. presented a novel regenerative absorber. With vibration amplitudes varying from 1 to 5 mm and frequencies varying from 1 to 2.5 Hz, the peak efficiency can reach 52% and the average efficiency is approximately 40%. By utilizing a ball screw and two overrun clutches, Liu et al. proposed a mechanical-motion-rectifier-based energy harvester with an efficiency range of 41–65% in 2.5 Hz-7.5 mm excitation [11].

4. DESIGN CALCULATIONS OF REGENERATIVE SHOCK ABOSRBER

The first step is designing the damper cylinder. Before designing we need to take some basic assumptions which are as follows:

- Material: Structural steel
- Max pressure inside cylinder (Pi) = 53 Mpa
- Inside diameter of cylinder (Di) = 60 mm
- Tensile stress of structural steel (σt) = 215 Mpa
- Poisson's ratio (μ) = 0.29

By using Clavarino's equation [12] for design of pressure vessels:

$$t = \frac{Di}{2}\left(\sqrt{\frac{\sigma t+(1-2\mu)Pi}{\sigma t-(1+\mu)Pi}}-1\right) \text{----------(Eqn 1)}$$

$$t = \frac{60}{2}\left(\sqrt{\frac{215+(1-(2*0.29)*53)}{215-(1+0.29)*53}}-1\right)$$

$$t = 8.1612\, mm \cong 8\, mm$$

Therefore, thickness of Damper Cylinder (t) = 8 mm and Outer diameter of Damper Cylinder (Do) = Di + 2t = 60 + 2(8) = 76 mm.*

Now, the next step would be designing of piston and piston rod.

1. Diameter of Piston:

● Piston diameter = inner diameter (Di) – allowance for oil seals (≅ 2 mm) ----------**(Eqn 2)**

● Piston diameter = 60 – 2 = 58 mm

2. Diameter of Piston rod: Usually Piston rod diameter for monotube dampers is 0.4 times the piston diameter. Therefore, Diameter of piston rod = (0.4*58) = 23.2 mm ≅ 23 mm

Now, calculations for estimation of damping force is needed to be done according to load variation. The equation [14] used for finding the right damper is as follows: -

International Journal of Scientific Research in Engineering and Management (IJSREM)
Volume: 05 Issue: 05 | May - 2021 ISSN: 2582-3930

$$Damping\ force = \frac{energy\ per\ stroke(N-m)*correction\ factor}{stroke\ (mm)} * 1000$$ ----------**(Eqn 3)**

According to the formula, we need to calculate energy per stroke. Considering equation for inclined loading, with angle 26^0 (standard), energy per stroke is given as:

$E = mgh + mgs$ ----------**(Eqn 4)**

Here m = impact mass = 200 kg (designing suspension for 200 kg load)
g = acceleration due to gravity = 9.81 m/s2
s = acceleration height = 0 (as suspension is joined with chassis)
h = damping distance = stroke * $\sin(26^0)$= 0.04*$\sin(26^0)$= 0.017 m

$E = 200 * 9.81 * 0.017 + 200 * 9.81 * 0$

Therefore, ***E*** = 33.354 N-m

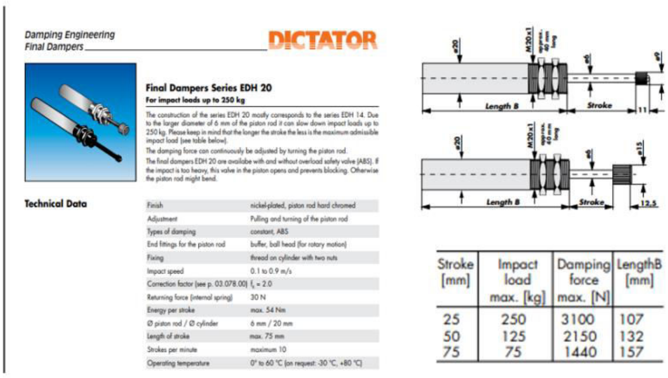
Now to evaluate damping correct factor, we will be using the equation which was proposed by Priestly in his research paper [13] "Damping correct factors for horizontal ground motion spectra" which is as follows:

$$DCF = \left[\frac{10}{5+\varepsilon}\right]^{0.25}$$ ----------**(Eqn 5)**

For underdamped system, ε= 0.4
Therefore, putting ε=0.4 in above equation;

$$DCF = \left[\frac{10}{5+0.4}\right]^{0.25} = 1.16$$

For calculation of stroke length, catalogue of DICTATOR TECHNIK-SELECTING THE RIGHT DAMPER [14] was used. By interpolation, calculated stroke length came out to be 40 mm for impact load of 200 kg. The corresponding length of cylinder was 122 mm.


Damping Engineering
Final Dampers
DICTATOR

Final Dampers Series EDH 20
For impact loads up to 250 kg

The construction of the series EDH 20 mostly corresponds to the series EDH 14. Due to the larger diameter of 6 mm of the piston rod it can slow down impact loads up to 250 kg. Please keep in mind that the longer the stroke the less is the maximum admissible impact load (see table below).
The damping force can continuously be adjusted by turning the piston rod.
The final dampers EDH 20 are availabe with and without overload safety valve (ABS). If the impact is too heavy, this valve in the piston opens and prevents blocking. Otherwise the piston rod might bend.

Technical Data

Finish	nickel-plated, piston rod hard chromed
Adjustment	Pulling and turning of the piston rod
Types of damping	constant, ABS
End fittings for the piston rod	buffer, ball head (for rotary motion)
Fixing	thread on cylinder with two nuts
Impact speed	0.1 to 0.9 m/s
Correction factor (see p. 03.078.00)	f_s = 2.0
Returning force (internal spring)	30 N
Energy per stroke	max. 54 Nm
Ø piston rod / Ø cylinder	6 mm / 20 mm
Length of stroke	max. 75 mm
Strokes per minute	maximum 10
Operating temperature	0° to 60 °C (on request: -30 °C, +80 °C)

Stroke [mm]	Impact load max. [kg]	Damping force max. [N]	LengthB [mm]
25	250	3100	107
50	125	2150	132
75	75	1440	157

Fig -3: Dictator Technik-Selecting the Right Damper Catalogue

Now energy per stroke = 33.354 N-m; correction factor = 1.16 and stroke length = 40 mm

$$Therefore\ Damping\ force = \frac{energy\ per\ stroke(N-m)*correction\ factor}{stroke\ (mm)} * 1000$$

$$Damping\ force = \frac{33.354(N-m)*1.16}{40(mm)} * 1000 = 967.266\ N \cong 1000\ N$$

Therefore, damping force = 1000 N.

There were some other design parameters which are as follows:

1. Thickness of piston = 12 mm
2. Thickness of floating piston = 12 mm
3. Diameter of holes in piston = 4 mm
4. Number of holes in piston = 8 (as 4 Non Return Valve will be fitted in one direction and 4 Non Return Valve in other direction)
5. Volume of oil = $\frac{\pi}{4}D^2L = \frac{\pi}{4}0.06^2 * 0.068 = 1.9926 * 10^{-4}\ m^3$

Now, the next step is to design helical spring [15] for floating piston. We assume that that 2000 N load is acting on the suspension system out of which 1000 N force will be damped by the monotube structure arrangement and the remaining 1000N will be the load acting on spring attached to floating piston. Therefore load acting on spring would be F= 1000 N. Considering initial displacement of spring δ = 10 mm, Free length = 40 mm, Compressed length = free length - δ = 40 – 10 = 30 mm and Material as Cold drawn steel wire we can deduce the following:-

- Permissible shear stress induced inside spring τ = 0.5 S_{ut}

For cold drawn steel wire, S_{ut} = 1050 N/mm^2
Therefore, τ = 0.5 * 1050 = 525 N/mm^2

- Spring index C = 6 [assumption]
- Wahl Factor:

$$k_w = \frac{4c-1}{4c-4} + \frac{0.615}{c}$$ ----------**(Eqn 6)**

$$k_w = \frac{4(6)-1}{4(6)-4} + \frac{0.615}{6} = 1.2525$$

- Mean coil diameter:

$$T = \frac{k_w*8*F*C}{\pi d^2}$$ ----------**(Eqn 7)**

$$525 = \frac{1.2525*8*1000*6}{\pi d^2}$$

$$d = \sqrt{\frac{1.2525 * 8 * 1000 * 6}{\pi * 525}}$$

***d* = 6.037 ≅ 6 mm**

- Mean diameter of spring

Spring index C = $\frac{D}{d}$ ----------**(Eqn 8)**

D = d * C = 6 *6 = 36 mm

- No of active coils

$$\delta = \frac{8FN_tD^3}{Gd^4}$$ ----------**(Eqn 9)**

Take G = 81370 N/mm^2 for cold drawn wire

$$N_t = \frac{G\,d^4\delta}{8FD^3} = \frac{81370 * 6^4 * 10}{8 * 1000 * 36^3}$$

N_t = 2.82 ≅ 3 *coils*

- Assuming plane end spring;

International Journal of Scientific Research in Engineering and Management (IJSREM)
Volume: 05 Issue: 05 | May - 2021 ISSN: 2582-3930

No of active coils = Total no of coils = 3
Therefore, Inactive coils = 0

- Solid length = $N_t * d = 3 * 6 = 18$ mm
- Total gap = compressed length – solid length = 30 mm – 18 mm = 12 mm
- Gap between 2 coils = $\frac{Total\ gap}{Nt-1} = \frac{12}{3-1} = 6$ mm
- Pitch = $\frac{free\ length}{Nt-1} = \frac{40}{3-1} = 20$ mm

Now, selection of fluid for dampers based on the viscosity of fluid will be done by using the equation for laminar flow of fluid.
Damping force inside damper is given by;

$$F = (P_1 - P_2) * A$$

Therefore, $P_1 - P_2 = \frac{F}{A}$ -----------**(Eqn 10)**
Equation of pressure difference for laminar flow is given by,

$P_1 - P_2 = \frac{32*\mu*V_{avg}*l}{D^2}$ ------------**(Eqn 11)**

Where; D= Equivalent diameter of flow
μ = Dynamic Viscosity
l = Length of flow
V_{avg} = Velocity of piston
Using these equation, we calculate the viscosity = 23 mm^2/s (kinematic)
So we choose our fluid as **Sasol Damper Oil 37** [16] as it has very high viscosity index.

5. DESIGN OF GENERATION MODULE

Generation module is based on faraday's law of electromagnetism which states that "*a voltage is induced in a circuit whenever relative motion exists between a conductor and a magnetic field and that the magnitude of this voltage is proportional to the rate of change of the flux*".

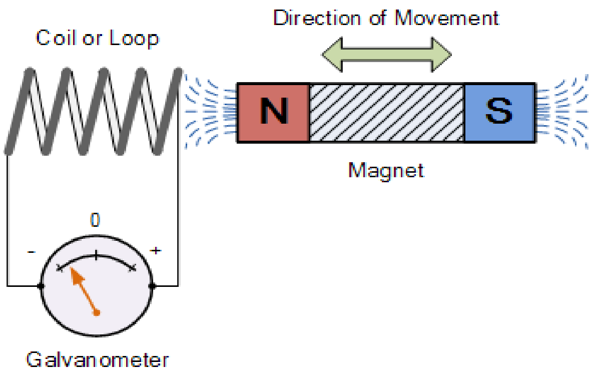


Fig-4: Faraday's Law of Electromagnetism

To design the generating module first we need to identify and select the most suitable magnet array configuration. There are four different ways in which magnets can be arranged to produce different strength of flux.

These four configurations are as follows and are shown in fig 5:

A. Axially

B. Axially and radially (Halbach array)

C. Radially inward and outward

D. Radially outward

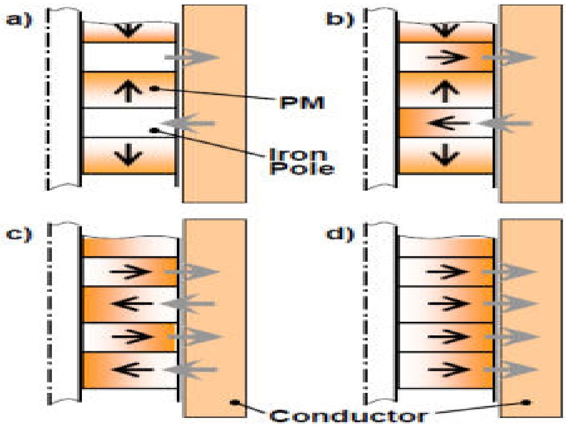


Fig-5: Different configurations of magnetic array

Selection of configuration A was done as it uses less magnet material and it has a high value of radial magnetic flux density (B_r) as we can see in the table 1:

Table -1: Magnetic Flux Density for different configuration's

Configuration	(a)	(b)	(c)	(d)
Max(B_r) [T]	2.087	1.627	1.315	0.685
Max(B_r) in the gap[T]	0.68	0.81	0.43	0.18
Damping Coefficient (C) [Ns/m]	52.47	82.46	19.86	3.9

Now, for sizing of magnets, a research paper titled as "*SIMULATION ON EDDY CURRENT DAMPER AND ITS REGENERATIVEBEHAVIOUR IN SHOCK ABSORBER FOR ELECTRIC VEHICLE"BY YONG YEW RONG* [17] *was referred.*

In this paper, the size of magnet was determined by magnetic circuit analysis. The magnetic analysis was assumed to have no leakage of flux & no fringing magnetic fields. The analysis was performed for one pole pair only. The equivalent 2D half lumped circuit is show in the figure below: -

International Journal of Scientific Research in Engineering and Management (IJSREM)
Volume: 05 Issue: 05 | May - 2021 ISSN: 2582-3930

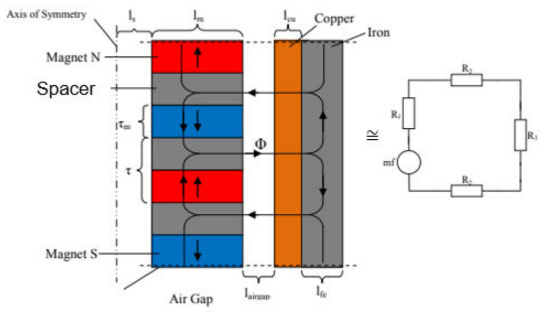


Fig-6: Equivalent 2D half Lumped circuit

Here, T = Thickness of magnet and pole, mm

T_m = Thickness of magnet, mm

l_m = length of magnet core, mm

l_s = length of air core, mm

l_g = length of air gap, mm

l_{cu} = length of copper, mm

l_{fe} = length of iron, mm

μ_i = absolute permeability of steel, Hm-1

μ_o = relative permeability of free space, Hm-1

μ_{cu} = absolute permeability of copper, Hm-1

R_1,R_2,R_3= Reluctance of circuit

M_f = magneto force produced by permanent magnets

The dimensions and their corresponding values are given in table 2:

Dimension	Material	Value	Comment
T_m	NdFeB (N52 grade) (High coercivity force and reasonable cost)	25 mm	• B_r= (1.42 – 1.48) T • Energy product (BH)max = 390-422 • Operating Temp Max = 80^0C
T	Pole made of 1018 steel	35 mm	• 1018 steel has good permeability (μ_i=875 * 10^{-6} Hm^{-1})
l_m	Permanent magnet	14 mm	• Inner diameter (ID = 10 mm) • Outer diameter (OD = 38 mm)
l_s	Air core	2.5 mm	
l_g	Air gap	5 mm	
l_{cu}	Copper cylinder	5 mm	
l_{fe}	Iron cylinder	1 mm	Decrease in reluctance is very small.
D_{cu}	35SWG enamelled copper coil	5 mm	3 phase copper windings

Table -2: Dimensions and their values

Three phase power generation concept was used for energy regeneration as it has constant power flow and lower losses. Figure below shows the coil arrangement: -

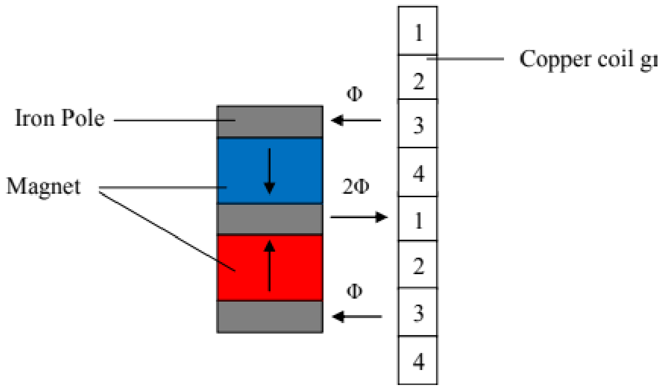


Fig -7: 3 phase power generation concept

Now, energy generated due to relative motion between coils and magnets is given by:

$E_i = B\,l\,V$ ----------**(Eqn 12)**

$I = \frac{E_i}{R} = \sigma A_w B_r V$ -------**(Eqn 13)**

$P = E_i I = \sigma l A_w B_r^2 V^2$---------**(Eqn 14)**

Here,

E_i = EMF voltage, V

I = maximum induced current (short circuit), A

R = resistance of wire, Ω

σ= electrical conductivity of wire, S/m (5.96 * 10^7 S/m)

A_w = Area of conductor wire, m2

B_r = radial magnetic flux, T/m2

V = vertical velocity, ms^{-1}

P = power produced, W

From the references of the research paper by *YONG YEW RONG* it was found that:

A. If the oscillation is 1 Hz & Maximum speed of 1 m/s then the voltage generated is about 8 volts and power generated depends upon resistance of coil and can be upto 0.23 watts per coil.

B. If the oscillation is 20 Hz & Maximum speed of 3 m/s then the voltage generated is about 25 volts and power generated depends upon resistance of coil and can be upto 2.3 watts per coil.

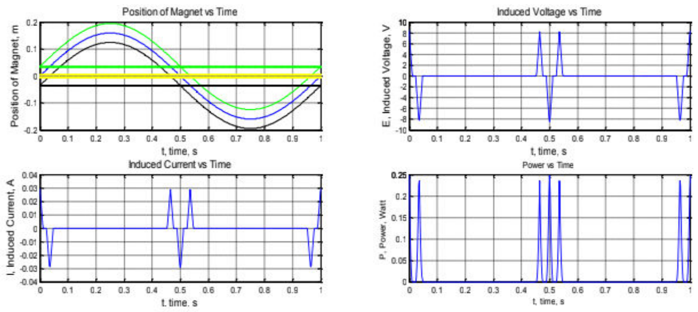


Fig -8: Combination of graph for oscillation frequency = 1 Hz and initial velocity = 1 m/s

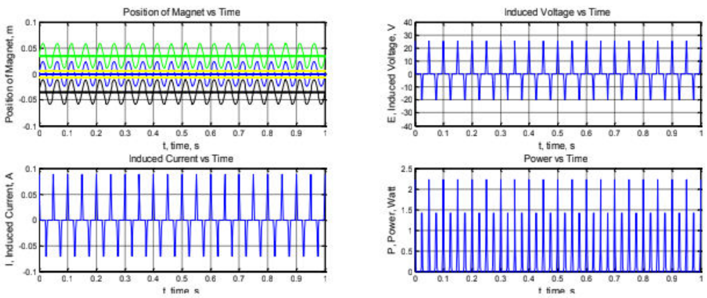


Fig -9: Combination of graph for oscillation frequency = 20 Hz and initial velocity = 3 m/s

6. CAD MODEL AND WORKING

The cad modelling was done using Solidworks software. Figure 10 shows the Cad model of monotube shock absorber without the generator module.

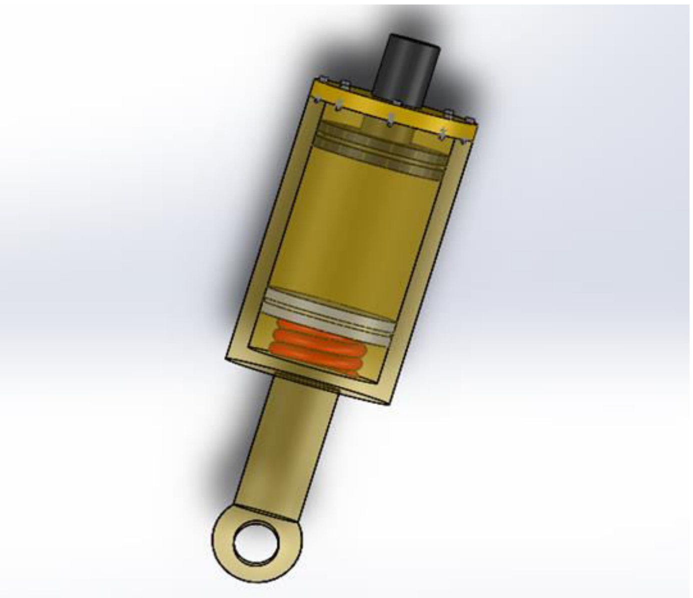


Fig-10: Cad model of Monotube shock absorber without generating module

Fig 11 and 12 show the Cad model of regenerative shock absorber.

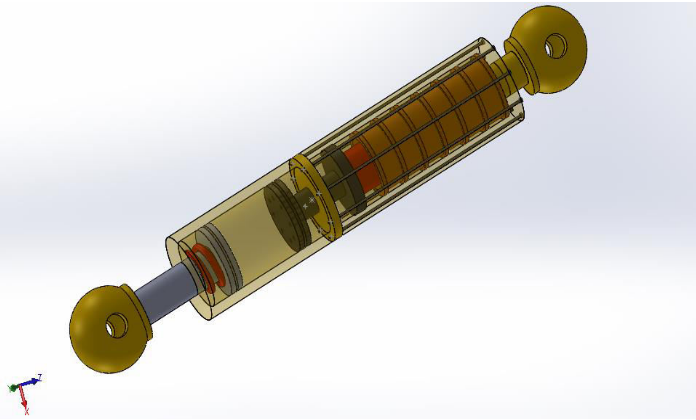


Fig-11: Regenerative shock absorber assembly with generating module

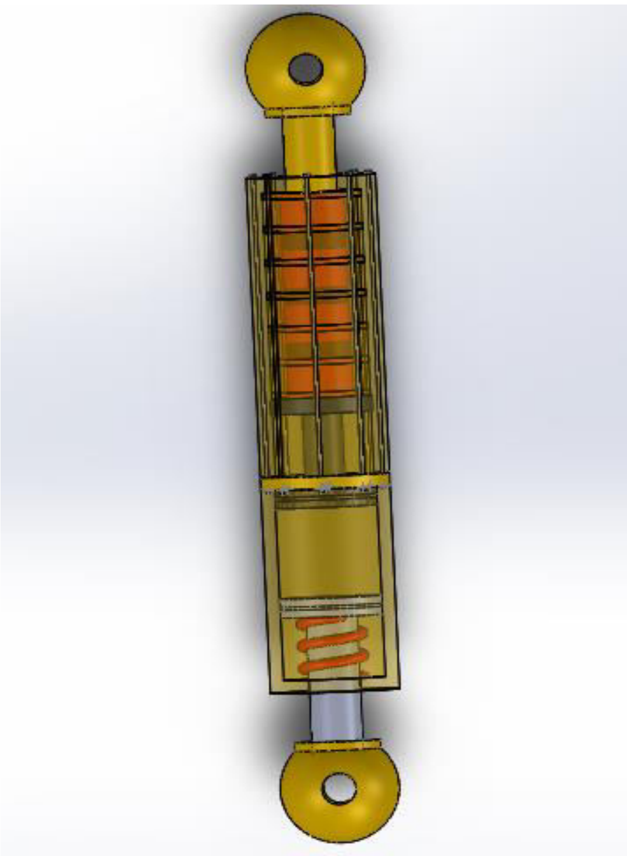


Fig-12: Regenerative Shock Absorber assembly front view

When potholes or any surface irregularity is there the tyres will try to move up and down and so this suspension system will try to stabilize the automobile and ensure passenger comfort. Shock absorbers work on the principle of fluid displacement on both the compression cycle and expansion cycle. The compression cycle controls the vehicle's unsprung weight and the expansion cycle controls the heavier sprung weight. In the compression cycle, the piston moves downward and compresses the hydraulic fluid in the chamber which is situated below the piston. In this cycle or downward movement, the fluid flows to the upper chamber from down chamber through piston. Some of the fluid also flows into reverse direction through the compression valve. Flow is controlled by valves in the piston. In the extension cycle, the piston moves upwards towards the top of the pressure tube. The upward movement results in the compression of the fluid in the chamber lying above the piston. The extension cycle generally provides more resistance than compression cycle. As the piston moves up and down, the Permanent magnet linear generator generates electricity and electricity produced is stored in capacitors or batteries to meet various energy requirements in automobiles.

7. FUTURE SCOPE AND CONCLUSIONS

Regenerative shock absorber has met its primary objective of producing a sufficient amount of regenerative energy (i.e. electrical energy) from the heat energy lost in dampers used to power various car accessories and equipment's. Currently the batteries of automobiles are charged using an alternator which is attached to crankshaft, so around 4 % of fuel consumption is utilized for this. This suspension system can be an efficient energy solution for recharging of E-Vehicles and for charging of batteries. If we install this regenerative shock absorber to all 4 wheels then we can generate high amount of energy which can be used to power car auxiliaries like AC's. This regenerative system can also be used in high load vehicles like trucks and buses due to their high power requirements. Although many researchers have been working on development of regenerative shock absorbers using various electrical and mechanical systems but face some challenges from the view point of stability, performance, complexity, vehicle integration and sufficient energy generation. A further research is needed to address this issues for designing a simple & efficient regenerative shock absorber.

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