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DESIGN AND ANALYSIS OF LINEAR GENERATOR FOR USE IN AUTOMOBILE SHOCK ABSORBER

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ABSTRACT

Significant amount of energy is lost in conventional hydraulic Shock Absorber. By using a linear generator in an automobile Shock Absorber, part of this energy can be harvested. This paper analyses design, simulation and working of a Linear Generator for use in automobile shock absorber. The presented Linear Generator has four phases and it uses rare earth permanent magnets. Static FEA has been performed for maximizing flux density in the air gap of the Linear Generator. Matlab model of the linear generator is created for calculating electrical energy generated, braking force on the armature coils, time constant and other parameters. While selecting the armature coil parameters due consideration is given to the required damping factor and electrical energy generated. Finally a scaled model of the Linear Generator has been fabricated and tested on a test rig. Electromagnetic damping force in the linear generator is observed to have On-Off effect. When used in Shock Absorber, this will result in greater variation of forces transmitted from tyre to the road. Damping factor offered by electromagnetic damping is found to be of non linear nature. The presented Linear Generator is able to harvest up to 60-80 W of energy, for suspension velocities of 0.1-0.2 m/sec.

1. INTRODUCTION

Conventional Shock absorbers consist of an elastic element connected in parallel with a dissipitative element. Viscous damper which is used as dissipitative element converts kinetic energy of vibration in to heat. Various researchers have attempted to build regenerative Shock Absorber by replacing dissipitative element by a linear generator. Zhen *et al* [4]has presented design of an electromagnetic shock absorber with two columns of cylindrical Permanent magnets and two groups of armature coils. The author claims that significant amount of power can be harvested from the design, but it has been supported with experimental findings. Zuo *et al* [7] have presented four phase linear generator design for use in vehicle shock absorber. Half scale model was able to generate up to 8W of energy for suspension velocity of 0.25-0.5 m/sec. The author have not highlighted on-off feature of the electromagnetic damping force. Goldner *et al* [13] have presented a linear generator with two layers of rare earth permanent magnets for harvesting the energy lost in Shock Absorber. Magnetic field of two layers is superimposed to obtain high flux density in the air gap of linear generator. Higher magnetic flux density increases the energy harvesting efficiency of the Shock Absorber. Gupta *et al* [11] have compared use of linear generator and rotary generator for energy harvesting in vehicle Shock Absorber. The authors have experimentally observed rotary D.C. generator is harvesting more amount of energy that that of linear generator.

This paper aims to design and validate a linear generator for use in automobile Shock Absorber. In designing the shock absorber due consideration has been given to the weight of the generator, damping factor achieved and energy generated by the same.

2. DESIGN AND ANALYSIS

For effective utilization of stroke length, and for minimizing electrical energy loss, configurations with shorter primary (coil windings) than that secondary (permanent magnet and pole pieces) is preferred for present linear Generator. Eight disc shaped permanent magnets as shown in figure 1 are proposed for use in the linear generator. Inner pole pieces are used in between the magnets as shown in figure 1. Outer pole piece is concentric with the magnets and is tubular in shape. Also since movement of coil in the magnetic field is likely to come across flux reversal, four phase armature coils are used. The voltage is induced in the armature coils, as they move relative to the magnets. The generated voltage is rectified by using diode Bridge rectifier.

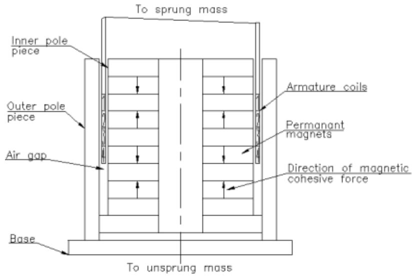

Figure 1. Arrangement of Linear Generator

2.1. Finite Element Analysis

Details of the disc shaped permanent magnets for use in the linear generator are as follows, Outer diameter of magnets: - 100mm, Inner diameter of magnets: - 30mm, Thickness of magnet: - 12mm Material:– N37 (Fe-Nd-B), Pole pieces material: - M.S., Static electromagnetic FEA has been performed with ANSYS to find the values of following dimensions that give maximum magnetic flux density in the air gap of linear generator:- Inner pole piece thickness -Inner pole piece outer diameter-Outer pole piece thickness. After little iteration, the dimensions that give maximum flux density in the air gap are obtained for inner and outer pole piece thickness of 10mm. Following parameters of the Armature coils have been selected such that the linear generator will harvest maximum energy and offer suitable braking force on armature coils.

- Armature Copper wire diameter (d_w) - Number of copper wire turns in each phase (N_c)

2.2. Modeling of Linear Generator

Detailed model of the linear generator is constructed in MATLAB Simulink. The input relative displacement is given as sine function of amplitude 20mm, whereas relative velocity is provided as derivative of the displacement.

3. SIMULATION OF THE LINEAR GENERATOR

Numbers of iterations are performed with following values of coil diameter. d_w= 0.2, 0.4, 0.8, 1.0 and 1.2mm. Numbers of armature coil turns (N_c) are calculated from filling factor and coil diameter. Figure 2 shown variation of damping factor for the selected coil diameters at various velocities. Damping factor depends on current in the armature coil. It can be seen from the graph that damping factor is maximum for armature coil diameter 0.4mm. As coil diameter is further increased, damping factor reduces. Non linearly of the damping factor is shown by figure 3.

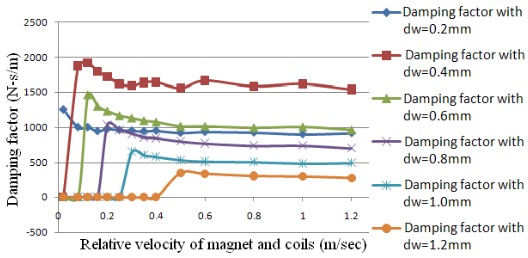

Figure 2. Damping factor for various coil diameters

Suitable damping factor for supporting mass of 350 Kg for heave natural frequency of 1.2 Hz is 2000 N-s/m. Following combination gives close value of damping factor. Also for these values, energy generated by the Linear Generator is highest.Armature coil diameter = 0.3760 mm (SWG 28.000), Number of turns per phase in the armature coils = 120 nos., Number of armature coils per phase = 2 nos., Total number of Armature coils = 8 nos.

3.1 Simulation of the Linear Generator for selected coil configurations

Dimensions of the Linear Generator are decided from FEA analysis for maximum flux density in the air gap. Whereas coil diameter and number of turns in armature are decided for required damping factor and better efficiency.

Table 1 shows details of the full scale linear generator.

Outer dia. of magnet	100mm
Inner Dia. of magnet	30mm
Thickness of magnet	12mm
Number of permanent magnets used	8
Outer dia. of inner pole piece	100mm
Inner Dia. of inner pole piece	30mm
Thickness of inner pole piece	12mm

Figure 3, shows voltage plot for phase 1-3, phase 2-4 and when all the phases are combined. In this case relative velocity of armature coils and magnets is 0.2 m/sec max. Similarly figure 4, shows voltage plot for phase 1-3, phase 2-4 and when all the phases are combined. In this case relative velocity is 0.3 m/sec max. Even though input displacement and velocity is sinusoidal, output voltage is not sinusoidal. Output voltage is rather pulsating in nature. Also frequency of the output voltage is not same as of input frequency. Output frequency depends upon thickness of the magnets and pole pieces. Voltage increases with increase in relative velocity between coil and magnets. 4 However if used for battery charging, the current will not flow in to the battery continuously, but rather intermittently, when the generated voltage becomes higher than battery threshold voltage.

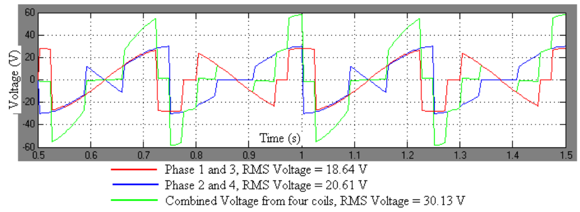

Figure 3. Voltage plots for relative velocity of 0.2 m/sec max.

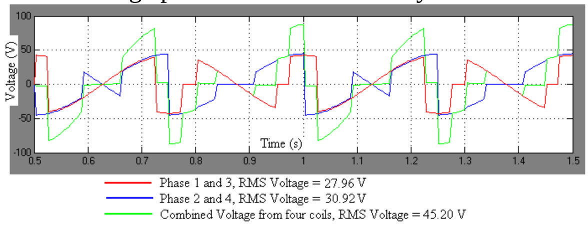

Figure 4. Voltage plots for relative velocity of 0.3 m/sec max.

Braking force on the armature coil opposes relative movement of the armature coil and magnet. Time constant is the delay between movement of the coil and current in the same. Higher time constant will affect Shock Absorber Performance, since it will create phase lag between damping force and movement of the sprung mass. Effect of the time delay is incorporated in Matlab model by using delay signal.

Figure 5 shows damping force for relative velocity of 0.2 m/sec max. As relative velocity increases damping force also increases. Damping factor achieved with the present linear generator is non linear in nature. For lower suspension velocities, when the generated voltage is lesser than threshold voltage of rectifying diodes, no current flows through coils. As armature coils comes across flux reversal in the air gap, voltage reduces to zero and it again increases. Because of this damping force also becomes zero and it again increases.

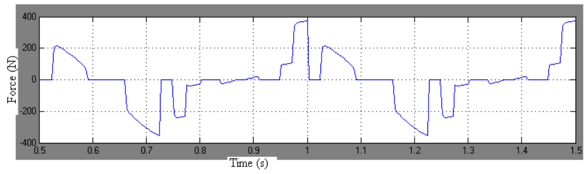

Figure 5. Electromagnetic damping force for relative velocity of 0.2 m/sec

Damping factor depends on whether the generator is acting in shunt or regenerative mode. Proper choice of shunt resistant is necessary to reduce the difference in damping factors in the above two modes. Above discussed factors contribute to the non linearly of damping factor.

As seen from figure 5, damping force has On-Off effect. Total voltage generated by the armature coils is as shown in figures 4, which is pulsating in nature. Current flows in the armature coils, only when voltage generated by the coils is sufficient to overcome threshold voltage of rectifying diodes, resistive and inductive voltage drops.

4. EXPERIMENTAL RESULTS

A reduced scale model of the linear Generator is fabricated with dimensions as shown in table 2. Static FEA has been performed to determine dimensions of pole thickness for maximum air gap flux density. Residual magnetic flux density of 0.25 to 0.50 T is obtained in the air gap for the dimensions of pole pieces as shown in table 2. Armature of the generator is given with sinusoidal displacement relative to the magnetic field, as shown in figure 9. Maximum amplitude of this sinusoidal displacement is 20mm. Windings of phase 1 and phase 3, are connected such that the net voltage in the both the phases is added. Phases 1 and 3 are connected to the rectifier bridge, and the current is passed through a shunt resistance. Now when current is flowing through the armature, voltage across phases 1 and 3 is measured by using storage type oscilloscope. Also current is measured by using digital multimeter. Similarly voltage across phases 2 and 4 is measured, when the current is flowing through the shunt resistance. Storage type oscilloscope is used for this voltage measurement. MATLAB model as discussed earlier is provided with the parameters of reduced scale model of linear generator, as shown in table 1. Experimentation is done to measure voltage and current across the armature winding for the following frequencies; 1Hz, 2 Hz and 4 Hz.During the experimentation, voltage across coils at 1, 2 and 3 Hz is measured with results summarized as shown in table 2. RMS values of voltage across the coil set measured experimentally are matching closely to the values calculated by simulation. As reveled by experimentation, frequency of the output voltage is not same as of frequency input excitations. But it depends on dimensions of pole pieces and magnets. This is because the armature coil comes across flux reversal after it moves through distance equal to half the thickness of the pole piece. As it comes across flux reversal, voltage in the coil becomes zero and changes its sign form positive to negative and vice versa. Also even though the input excitations are sinusoidal, the output voltage plots are not sinusoidal, but they are of pulsating nature.

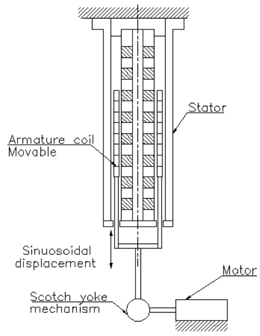

Figure 9. Experimental set up for the linear generator

Frequency (Hz) 20mm Peak displacement	Simulation Voltage (V)		Experimental Voltage (V)		Simulation Current (Amp)		Experimental Current (Amp)
	Peak	RMS	Peak	RMS	Peak	RMS	RMS
1	3	1.37	3	1.35	0.079	0.044	0.05
2	6	2.4	6	2.7	0.090	0.06	0.07
3	8	3.5	7.8	3.2	0.17	0.09	0.10

Table 2: Results for experimentation

5. CONCLUSION

In the presented study design, optimization and analysis of a linear generator for use in automobile shock absorber has been discussed. While designing the present linear generator damping factor, efficiency of the generator and weight of the structure has been taken considered. Results of simulation are matching closely to the experimental findings. The fabricated reduced scale Linear Generator is able to harvest peak energy of 0.8 - 1.2 W for suspension velocities of 0.1 – 0.2 m/sec. Full scale linear generator will be able to harvest electrical energy of 60-100W for suspension velocities of 0.1 to 0.2 m/sec, which are normally encountered on the road. Full scale electromagnetic Shock Absorber will offer damping force of 250- 500N for the above velocities. Frequency of the generated voltage depends on input frequency of excitation, thickness of magnets and pole pieces. Electromagnetic damping force shows On-Off effect, which needs to be further investigated, for its effect on safety and comfort of the vehicle.

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