Energy Harvesting Shock Absorber with Linear Generator and Mechanical Motion Amplification

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Abstract

Energy harvesting shock absorbers can generate about 15-20 W of electric power for normal suspension velocities. However, higher weight, fail safe characteristics and space limitations have restricted development of regenerative shock absorbers to research prototypes. Power to weight ratio of regenerative shock absorbers can be improved by incorporating motion amplification. In the presented work, an innovative design of energy harvesting shock absorber has been presented that uses motion amplification for improving harvesting efficiency. Apart from improving electric power, the proposed solution is fail safe and can be easily incorporated in existing vehicles with only marginal change in suspension layout. Study includes detailed numerical analysis for vibration transmissibility to investigate comfort and safety. Further, a prototype has been fabricated and experimentation has been performed to compute electric power generated and comfort. Simulations have been performed on real size model with utilization of harvested electric power which indicates about 19% of overall harvesting efficiency.

Keywords: motion amplification, electric power, energy harvesting, efficiency, numerical simulation

1. Introduction

Energy harvesting shock absorbers constitutes an electric generator, which is used as the dissipative element instead of conventional fluid damper and can harvest up to 15-20 W of electric power [1, 2]. However, lower power to weight ratio, bulky design, non-linear damping force and inferior fail safe characteristics have limited the scope of regenerative shock absorbers to research prototypes. Recently, hybrid version of regenerative shock absorbers use the electric generator as the power harvesting element, that supplements vibration energy dissipation, in addition to that of the fluid damper. Hybrid electromagnetic shock absorbers have better fail safe characteristics and can provide the necessary damping coefficient for a real size application with compact size [3].

Furthermore, velocity amplification is being preferred to ensure better power to weight ratio [4, 5].

Numerical simulation has been used to derive the optimum configuration of electric generators used in energy harvesting shock absorbers [6, 7]. The energy harvested by the shock absorber can be used for charging electric battery in the vehicle [8]. Indirect drive type of regenerative electric shock absorbers are preferred over that of the direct drive version due to compact design and efficient operation [9, 10]. Theoretical simulations on hydraulic electromagnetic shock absorber, implemented in a railway suspension, estimated that 300-500 W of peak power can be harvested [11, 12]. A hybrid regenerative shock absorber harvested 0.25 W of power for 0.004 m/s of suspension velocity [13]. Energy harvesting shock absorber with additional energy storage device can increase range of electric vehicles [14]. Electromagnetic regenerative shock absorber with rack-pinion mechanism and fluid elements can be used for amplification of the coil relative velocity [15]. Quarter car simulations and finite element analysis have been used to evaluate regenerative shock absorbers for power harvested and vibration isolation performance [16, 17].

Vibration energy dissipation by the electric generator used in real size shock absorber applications, is limited due to practical constraints on size and weight. Therefore, to make up the additional requirement of energy dissipation, a fluid damper is added to the system. Although number of hybrid shock absorbers has been reported in the literature, their practical implementation is limited due to the following reasons.

- Electromechanical damping force is non-linear in nature, accordingly comfort and safety is compromised with higher electromechanical damping force. However, reducing the damping also reduces power harvested. Therefore there is a need to increase the electrical power and at the same time keep the resultant vertical component of the damping force to minimum.
- Most of the indirectly driven electrical generators utilize mechanical gears which are prone to be damaged under parasitic loading conditions encountered in case of suspensions.
- Real case incorporation of the hybrid shock absorber needs to be demonstrated particularly in case of smaller C-segment car, to study the practical effect on comfort of the vehicle and fail safe characteristics.

An attempt has been made in the presented paper to overcome the above limitations of existing indirectly driven hybrid regenerative shock absorbers, with an innovative design, hereafter referred as Hydraulic ElectroMagnetic Shock Absorber (HEMSA). A link based mechanism has been used to drive a linear generator with amplified coil relative velocity. Numerical model of the shock absorber has been presented that estimates power harvested, comfort and safety of the vehicle. Further, a prototype has been fabricated and incorporated in a C-segment car suspension to experimentally evaluate electrical energy harvested and effect of the regenerative suspension on comfort of the vehicle.

2. Mathematical modelling

A quarter car model shown in Figure 1 has been used for numerical simulation of HEMSA,. It comprises of sprung mass (m_1), unsprung mass (m_2), suspension spring (stiffness: K_s), fluid damper (damping coefficient: C_s) and the tyre (with vertical stiffness: K_t). Further the link based amplification mechanism has been fitted between the sprung and unsprung masses. The amplification mechanism has links as illustrated in Figure 1 and it operates with vertical relative velocity between the sprung and un sprung masses to drive the linear generator assembly in horizontal direction. The linear generator assembly as illustrated in Figure 1 has the armature coils carried by one side of the amplification mechanism whereas the other side is connected to the magnet and spacer assembly. The presented arrangement ensures 320% amplification in the generator coil relative velocity. Governing differential equations for the system are given as:

$$m_1\ddot{z} = -K_s(z-y) - C_s(\dot{z}-\dot{y}) - F_{\mathrm{lg}} \sin\left[2\sin^{-1}\frac{h-|y-z|}{2l}\right] \tag{1}$$

$$m_1\ddot{y} = -K_t(y-x) + K_s(z-y) + C_s(\dot{z}-\dot{y}) + F_{\mathrm{lg}} \sin\left[2\sin^{-1}\frac{h-|y-z|}{2l}\right] \tag{2}$$

where:

F_{lg} – electromagnetic braking force on the linear generator coils,
l – amplification mechanism link length.

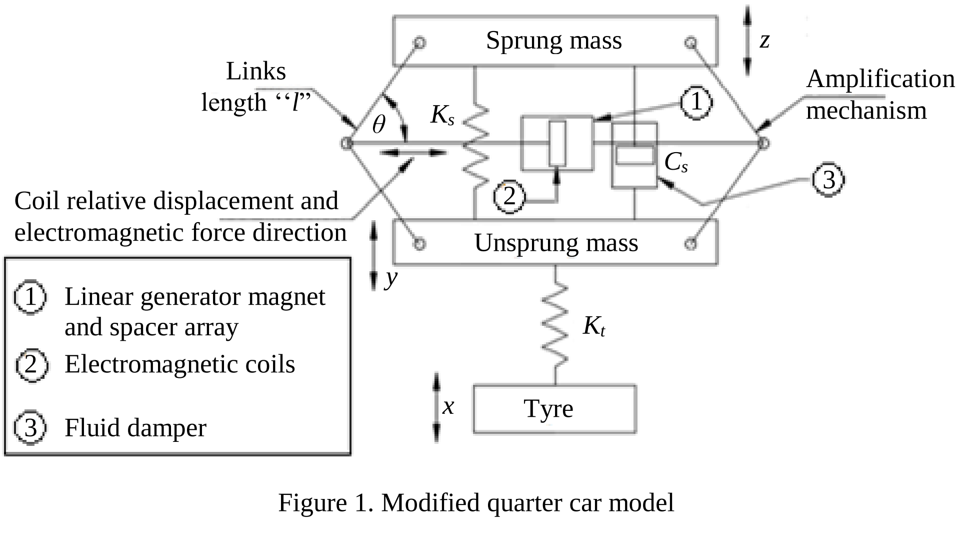

Figure 1. Modified quarter car model

Voltage across the load resistance is given as:

$$U_{tot} = IR_{total} = \left(\pi D_{avg}\ N_c B\dot{u}\right) - L_{coil}\frac{dI}{dt} \quad (3)$$

Voltage across the coils depends on average armature coil diameter in the linear generator (D_{avg}), number of copper wire turns in the armature (N_c), air gap magnetic flux density (B), coil relative velocity in horizontal direction $(\dot{u})$ and the coil inductance (L_{coil}).

The coil relative displacement in horizontal direction is given as,

$$u = \frac{h-(z-y)}{2\tan\left[\sin^{-1}\frac{h-(z-y)}{2l}\right]} - \frac{1}{2}\sqrt{4l^2-h^2} \quad (4)$$

where:

h – distance between the sprung and unsprung masses at equilibrium.

Simulations have been performed in MATLAB based on Equations (1)-(4). Vertical displacement of the tyre (x) have been experimentally measured for two types of road profiles and used in the theoretical model during the simulations.

3. Experimental and simulation results

Prototype HEMSA has been designed to suit rear suspension of C-size passenger car (Maruti Suzuki Zen Lxi), which has been used along with the existing helical spring (stiffness: 10.5KN/m) and fluid damper (mean damping coefficient: 880 Ns/m with damper asymmetry of 70/30). Available layout in the suspension allows 220 mm of vertical and 210 mm of horizontal space. The CAD model is illustrated in Figure 2, which includes amplification links, linear generator, engagement mechanism, lower support and upper support. For more elaborate details on design and fabrication of the linear generator used in electromagnetic shock absorbers, the interested readers should refer to our earlier publication [18]. Photograph of the prototype fitted in the vehicle is shown in Figure 3.

It is necessary to ensure effective rattle space of the fluid damper, irrespective of limitations of the linkage mechanism vertical stroke. This is ensured by spring loaded ball and pin in the engagement mechanism, as illustrated in Figure 2. In case the suspension stroke exceeds working limit of the amplification mechanism, the spring loaded ball disengages the mechanism from suspension movement. The linear generator assembly comprises of magnets, inner spacers and outer spacer with constructional details given in Table 1. The links with length of 95 mm ensure effective velocity amplification within the available space. Upper and lower supports ensure rigid fastening of the prototype assembly to the sprung and unsprung masses respectively.

Experimentation has been performed to evaluate electrical power harvested and comfort in the vehicle. The test vehicle was driven along two types of roads (referred as Type-1 and Type-2) and acceleration (at the tyre and sprung mass) have been measured with a vibration meter (Instrument: Svantek SVAN958 - four channel sound and vibration analyser) and two uniaxial accelerometers (SV 3185 D). Electrical power harvested by the linear generator has been evaluated by measuring voltage across electrical resistance (5 Ω) with an oscilloscope (Tektronix TDS 1001B).

Table 1. Details of the linear generator

Magnet and inner spacer outer diameter (inner diameter x outer diameter x thickness):	9mm x 12mm x 5mm (10 numbers)
Magnet material and coercive force	Ferrite, 254 kA/m
Outer spacer (inner diameter x outer diameter x thickness)	19mm x 22mm x 104mm
Material for inner and outer spacers	Mild steel
Armature copper wire diameter and number of turns	0.2 mm with 85 turns

Test vehicle set up with all the equipment is shown in Figure 4. Further, vertical acceleration measured at the tyre has been used in theoretical simulation to determine the sprung mass acceleration, electric power and tyre deflection from the numerical model. Experimental and simulation results for the sprung mass acceleration are shown in Table 2, which shows close agreement. Experiment was conducted to determine sprung mass acceleration without the prototype HEMSA fitted in the rear suspension and maximum acceleration was recorded to be 1.524 m/s^2. Safety criteria of the shock absorber has been evaluated by calculating the root mean square (rms) tyre deflection. Lower tyre deflection gives lesser variation in forces transmitted from tyre to the road and vice versa. Values of rms tyre vertical deflection for the prototype HEMSA have been calculated from numerical simulation and reported in Table 2. Further simulations performed with the theoretical model indicate that maximum rms tyre deflection for conventional fluid shock absorber (without prototype HEMSA) will be 3.51 mm.

Marginal increment in the acceleration (8%) and tyre deflection (7%) is attributed to the fact that presently the linear generator has been incorporated along with the existing fluid damper, which increases overall damping coefficient for HEMSA than that of the conventional fluid shock absorber. However, there is a need to redesign the fluid damper since electromagnetic damping is being assisting in energy dissipation. Simulation study indicates that the vertical component of electromagnetic force is about 20-25% than that of the braking force on the generator coils (i.e. F_{lg}). Linear generator coils are operated with amplified relative velocity (than that of the relative velocity between sprung and unsprung masses) to derive better power output and simultaneously only fraction of the electromagnetic force is transmitted as the vertical component, that influences comfort and safety. Thus HEMSA ensures more power output and effect of electromagnetic force on the vibration isolation is kept at minimum.

The peak power of the real size HEMSA can be significantly improved by replacing the ferrite magnets with high energy density rare earth magnets and improving number of copper wire turns. Literature indicates that maximum flux density in the linear generator air gap can be increased up to 0.7 T. Minor changes in the existing vehicle layout can facilitate redesign of amplification mechanism to ensure velocity increase up to 800% that of the suspension vertical velocity. These modifications will ensure that the real size HEMSA will ensure peak power of about 18-25 W for each of the shock absorber with an efficiency of 19.28%.

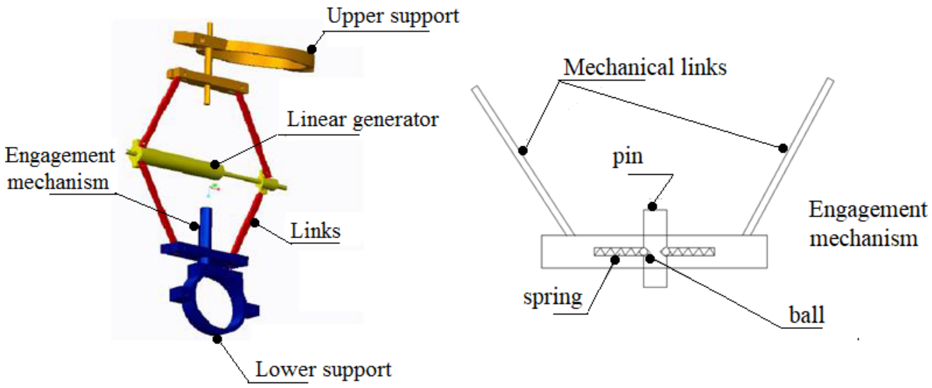

Figure 2. CAD model of the prototype with engagement mechanism

Figure 3. The view of EMSA prototype

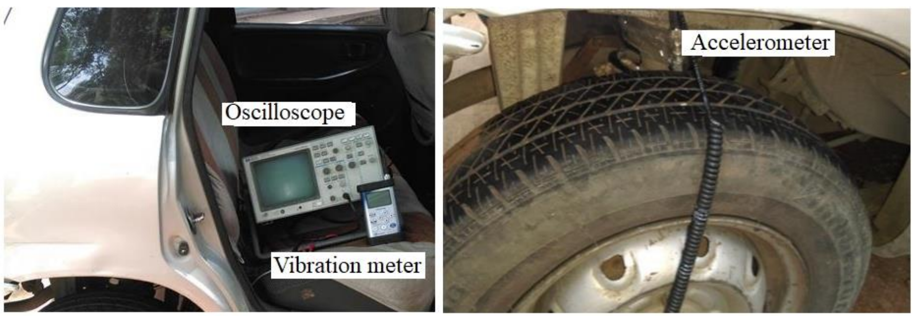

Figure 4. Test set up

Table 2. Experimental and simulation results for comfort, handling and electric power

Type of road	Vehicle speed [km/h]	Sprung mass peak vertical acceleration [m/s^2]		Peak electric power [mW]		Peak tyre displacement [mm]
		Therotical	Experimental	Therotical	Experimental	
Smooth Type 1	10	0.127	0.132	3.1	2.0	1.25
Smooth Type 1	20	1.218	1.356	8.2	6.5	2.84
Rough Type 2	10	0.282	0.355	6.2	5.1	2.38
Rough Type 2	20	1.580	1.673	28.0	20.0	3.81

4. Conclusion

The study presents design of an energy harvesting shock absorber (HEMSA) that uses amplification links to increase electrical power output. Results of numerical modelling has been presented to evaluate comfort, safety and electric power. Novel feature of the presented work includes design, fabrication, fitment and experimentation of the prototype HEMSA in a C-size passenger car rear suspension. The experimentation has been performed to determine acceleration transmitted and electrical power harvested by the energy harvesting shock absorber, when the vehicle travelled along two types of roads with different velocities. Vertical acceleration at the tyre has been measured with an accelerometer and used to evaluate the numerical model for validating the experimental data. Simulation and experimental results indicate that electrical power up to 21 mW can be harvested with only marginal increment in the sprung mass acceleration. In the event of the electric generator failure, fluid damper will provide minimum force ensuring better failsafe characteristics. The prototype has used ferrite magnets and existing rear suspension layout. However significant power of up to 18-25 W can be harvested from each of the shock absorber, with redesign of existing suspension layout for more vertical space for HEMSA and use of high energy rare earth magnets.

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