

Assessment of Vehicle Performances with Energy-Harvesting Shock Absorbers

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ABSTRACT

Energy-harvesting from vehicle suspensions has attracted a lot of attention recently due to its potential to recover large amount of kinetic energy which is traditionally wasted in oil shock absorbers, besides it can improve the ride comfort and road handling at the same time. Rotary electromagnetic mechanism has been a popular solution in the design of energy-harvesting shock absorbers and recently an innovative energy-harvesting shock absorber based on so-called mechanical motion rectifier (MMR) has been proposed, which converts the irregular bi-directional suspension vibration into unidirectional motion of the generator. Though it may offer advantages of higher mechanical reliability and harvesting efficiency, its influence on the whole vehicle dynamics is not known yet due to the nonlinearity of the MMR shock absorber. This paper presents an integrated model of a quarter car with a conventional or MMR-based rotary electromagnetic energy-harvesting shock absorber, and assesses the vehicle dynamics and energy-harvesting potential under various road conditions.

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INTRODUCTION

Considerable amount of kinetic energy is dissipated by the traditional shock absorbers in vehicle suspension and is a source worthy of attention for energy recovery. Energy-harvesting, or regenerative shock absorbers have been a research topic in both academia and industry for more than two decades. Different principles and designs of regenerative shock absorbers have been proposed and investigated, including electromagnetic suspensions and regenerative hydraulic suspensions. Based on the motion of the energy generator, the reported electromagnetic regenerative shock absorbers can be classified in two main categories, linear harvester and rotary harvester.

Linear harvesters are basically a linear generator in the shock absorber shape, which generates electricity from the relative linear motion between magnets and coils. Researchers [1,2,3,4] have done a lot of exploration on the design and optimization of such kind of shock absorbers and prototype test results are presented in literatures. Zuo *et al.* [5] designed a linear electromagnetic energy harvester and made prototype which was capable of generating more than 16 watts of energy from one shock absorber under 0.25 m/s root-mean-square (RMS) suspension velocity.

Besides the linear regenerative shock absorbers, the other type of electromagnetic regenerative shock absorbers is

rotary harvesters, which converts the linear suspension motion into oscillatory rotation of the generator through certain mechanisms, such as ball screw, rack and pinion, and hydraulic transmission, to generate electrical energy. Gupta *et al.* [6] compared a linear shock absorber with a rotary one and concluded that rotary shock absorbers have larger energy density. A few researchers [7,8,9,10,11] have developed and prototyped different types of rotary regenerative shock absorbers based on different mechanisms and presented results from lab experiments. Li and Zuo [12] proposed a new design based on rack and pinion mechanism and demonstrated the prototype with both lab and road tests. Besides the energy-harvesting function, electromagnetic shock absorbers with linear or rotary motors can also be used as actuators for active control or semi-active vibration control [13,14,15,16].

The rotary regenerative shock absorbers translate the linear suspension vibration into the bi-directional rotational oscillation of the generator and produce electrical energy. Since low-cost and off-shelf rotary generators are used, rotary harvesters can be more compact and cost effective than linear harvesters. However, the irregular oscillation causes numerous problems such as large impact on the mechanical components, backlash, and large friction in the transmission system, which will cause fatigue or even failure of the

components. The rack teeth were found to be worn out and broken quickly due to large impact force in Li's [12] early rack-pinion based prototypes. In addition, the bidirectional oscillating motion will produce an irregular AC voltage output at the terminals of a DC generator, which will make the storing and utilization of this energy more challenging.

To solve this problem, recently the authors [17] proposed an innovative energy-harvesting shock absorber based on a mechanism called MMR, which can convert the irregular bi-directional suspension vibration into unidirectional motion of the generator. The structure model of the MMR based shock absorber is shown in Figure 1. The bi-directional linear motion of the suspension is converted into bi-directional rotation of the shaft through the rack and pinion, and then converted into unidirectional motion of the gear head shaft through two roller clutches and bevel gears.

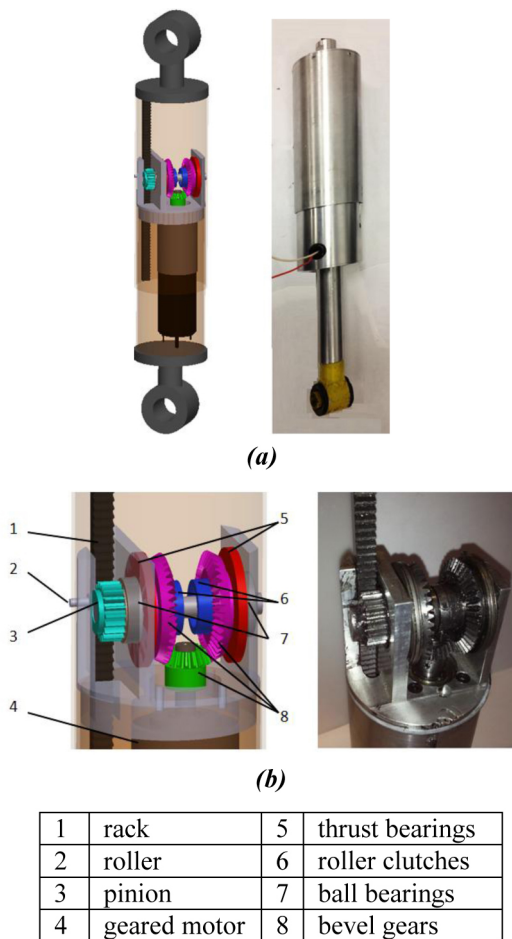


Figure 1. Comparison between 3D model and actual prototype, (a) overall view, (b) inner structure. [17]

This mechanism was found to be able to significantly improve the reliability of the structure by reducing the impact which happens at the moment of inversion of the generator's rotation, and at the same time increase the efficiency by decreasing the influences of friction. It also enables the electrical generator to rotate unidirectionally at relative

steady speed which would improve energy conversion efficiency and make the utilization of the electricity easier.

Although holding the merits of higher reliability and efficiency for harvesting energy, the influences of the regenerative shock absorbers on the whole vehicle dynamics are expected to be different from the one with traditional viscous shock absorbers, especially with the non-linearity of the MMR. Also, the amount of electrical energy which can be expected from such kind of regenerative shock absorbers when installed on vehicles traveling on typical roads still needs to be evaluated. This paper will present an integrated model of vehicle with rotary electromagnetic regenerative shock absorbers with and without MMR. The performances of both traditional shock absorber and regenerative shock absorbers will be evaluated and guidelines for designing such kinds of regenerative shock absorbers will be then presented.

MODELING OF VEHICLE DYNAMICS WITH REGENERATIVE SHOCK ABSORBER

The Quarter Car Model

Quarter car model can be used to analyze the dynamics of the vehicle under certain road excitations. For a quarter car model with regenerative shock absorber (as shown in Figure 2), the damping force is provided by the electromagnetic motor inside the regenerative shock absorber. The damping force provided by the MMR shock absorber is represented by F_d , then the dynamics of the model can be easily written as:

$$\begin{bmatrix} m_1 & 0 \\ 0 & m_2 \end{bmatrix} \begin{pmatrix} \ddot{x}_1 \\ \ddot{x}_2 \end{pmatrix} + \begin{bmatrix} k_1 & -k_1 \\ -k_1 & k_1 + k_2 \end{bmatrix} \begin{pmatrix} x_1 \\ x_2 \end{pmatrix} = \begin{pmatrix} F_d \\ k_2 Z - F_d \end{pmatrix} \quad (1)$$

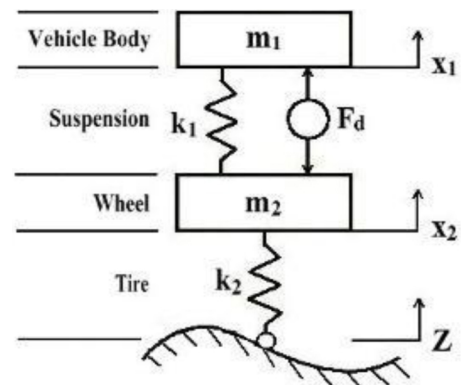


Figure 2. Schematic of quarter car model with semi-active shock absorber.

The Regenerative Shock Absorber Model

Rotary electromagnetic regenerative shock absorber concepts have been proposed and investigated for decades. The MMR based energy-harvesting shock absorber was proposed by the authors in [17], which can convert the irregular bi-directional suspension vibration into

unidirectional motion of the generator. The simplified schematics of rotary electromagnetic regenerative shock absorbers with and without MMR are shown in Figure 3.

As shown in Figure 3, non-MMR shock absorber converts two-direction linear motion of the shock absorber into two-direction rotation of the generator, which is described in [12], while the MMR based shock absorber converts two-direction linear motion into unidirectional rotation. One property of this kind of MMR shock absorber is its non-linear behavior. When the rotation velocity of the input shaft to the motion rectifier is smaller than the velocity of the output shaft, the roller clutches inside would disengage from the output shaft, resulting zero torque transmission.

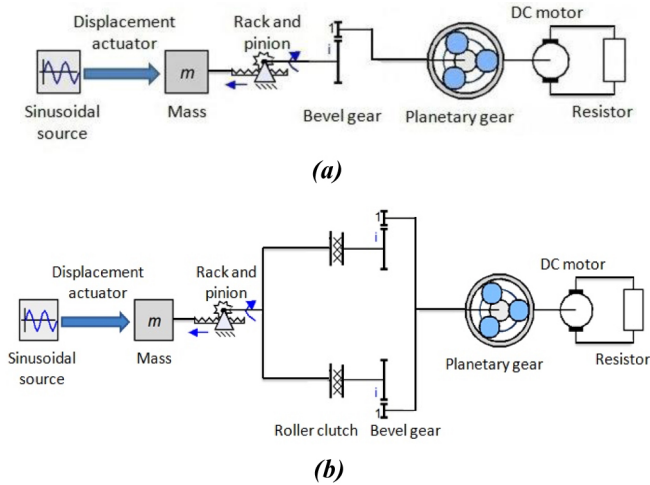


Figure 3. Simplified schematic of the (a) non-MMR and (b) MMR regenerative shock absorbers. [17]

When disengagement happens, the output shaft of the mechanical motion rectifier will keep rotating at a higher speed than the input shaft due to the kinetic energy stored on the inertia of the mechanical elements, such as, fly-wheel, gears and the rotor of the generator. However, this rotational speed will gradually decrease due to friction and electrical load connected to the generator. When the output shaft speed is again equal to the input shaft speed, the roller clutches get re-engaged and start transmitting torque to the generator. In the presented modeling, the friction effect has been neglected for simplicity purpose. Due to the small radius of the input shaft, which is 10 mm, the torque caused by friction is relative small compared with the motor's reaction torque.

For a DC generator, we can get the relation

$$V_{ef} = k_e * \omega \quad (2)$$

$$i = \frac{V_{ef}}{R} \quad (3)$$

where V_{ef} is the output voltage of the generator, k_e is generator constant, k_t is the torque constant, ω is the rotational speed of the generator, R is the total resistance in

the electrical circuit, including motor internal resistance and external load resistance.

Then we have

$$\tau_e = k_t i = k_t * \frac{V_{ef}}{R} = \frac{k_t k_e * \omega}{R} \quad (4)$$

When the MMR is engaged, the total force F_d provided by the shock absorber can be derived as:

$$F_d = -c * v - m_s * a \quad (5)$$

where v is the suspension speed, a is the acceleration of the suspension, $c = \frac{k_e k_t k_h^2 k_b^2}{R r^2}$ is the equivalent damping coefficient, k_h , k_b are the transmission ratios of the gearhead and bevel gears, m_s is the equivalent mass of all the inertias of the motor J_m , planetary gear head J_g and the larger bevel gears J_b , which is given as:

$$m_s = \frac{J_m k_h^2 k_b^2 + J_g k_b^2 + J_b}{r^2} \quad (6)$$

Detailed derivation of this relation can be found in [17]. When the MMR is disengaged, the torque transmitted to the motor falls down to zero, which means $F_d = 0$, then the rotational acceleration of the output shaft of MMR $\dot{\omega}_{out}$ is given as:

$$\dot{\omega}_{out} = \alpha_{out} = -\tau * \omega_{out} \quad (7)$$

$$\omega_{out} = \omega_{out0} * e^{-t/\tau} \quad (8)$$

where ω_{out0} is the rotational speed of the output shaft of MMR at the moment of disengagement, t is the time since the moment disengagement happens, τ is the time constant, which is given as:

$$\tau = \frac{m_s}{c} = \frac{R r^2 m_s}{k_e k_t k_h^2 k_b^2} \quad (9)$$

The rotational speed of the output shaft of MMR during engagement and disengagement is shown in Figure 4.

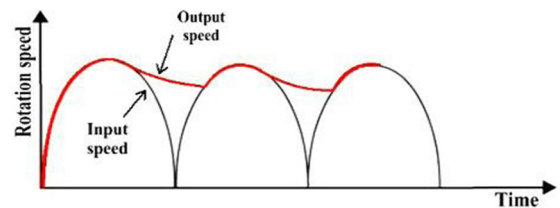


Figure 4. Disengagement inside the mechanical motion rectifier.