



A novel regenerative shock absorber with a speed doubling mechanism and its Monte Carlo simulation



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ABSTRACT

A novel regenerative shock absorber has been designed and fabricated. The novelty of the presented work is the application of the double speed regenerative shock absorber that utilizes the rack and pinion mechanism to increase the magnet speed with respect to the coils for higher power output. The simulation models with parameters identified from finite element analysis and the experiments are developed. The proposed regenerative shock absorber is compared with the regenerative shock absorber without the rack and pinion mechanism, when they are integrated into the same quarter vehicle suspension system. The sinusoidal wave road profile displacement excitation and the random road profile displacement excitation with peak amplitude of 0.035 m are applied as the inputs in the frequency range of 0–25 Hz. It is found that with the sinusoidal and random road profile displacement input, the proposed innovative design can increase the output power by 4 times comparing to the baseline design. The proposed double speed regenerative shock absorber also presents to be more sensitive to the road profile irregularity than the single speed regenerative shock absorber as suggested by Monte Carlo simulation. Lastly the coil mass and amplification factor are studied for sensitivity analysis and performance optimization, which provides a general design method of the regenerative shock absorbers. It shows that for the system power output, the proposed design becomes more sensitive to either the coil mass or amplification factor depending on the amount of the coil mass. With the specifically selected combination of the coil mass and amplification factor, the optimized energy harvesting performance can be achieved.

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1. Introduction

Since the fossil fuel has been largely consumed worldwide and caused a large amount of green-house gas emissions, it is necessary to replace the fossil fuel energy with renewable clean energy to protect the environment. Reducing the use of fossil fuel can greatly lower energy costs and reduce air pollution and climate change. In United States, 70% of the carbon monoxide, 45% of the nitrogen oxide and 34% of the hydrocarbon pollution are contributed by automobiles which are most powered by the fossil fuel [1]. Many studies have been conducted on reducing the fuel consumption of the vehicle by harvesting the energy that otherwise would have been wasted and dissipated as heat energy into the ambient. If this wasted thermal energy or vibration energy can be harvested and converted into the electric energy, not only will the travelling distance be extended,

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but also the air pollution will be reduced as well. The energy dissipation on the wheel system accounts for 22.5% of the total fuel combustion energy [2] and 31% of the energy dissipation on the wheel system is contributed by shock absorber. According to the estimation by Brandenburg et al. [3], up to 400 W can be recovered from four shock absorbers when a 1200 kg vehicle is driven at 60 mph on the highway, this account for 5% of the total engine output power required by the vehicle motion. The study of the regenerative shock absorber on the simulated road model has been conducted and the results concluded that up to 70% of the energy loss through the shock absorber can be harvested, which indicates a potential of the regenerative shock absorber for recovering the vibrational energy, enhancing the vehicle efficiency and sustainability [4].

Instead of dissipating the kinetic energy in a viscous damper as the heat loss, many researches have been conducted on utilizing electromagnetic generators to convert the kinetic energy into the electrical energy. It is proposed to connect the magnets and coils to the vehicle body and wheel assembly, respectively [1]. The electric current can then be induced directly as a result of the relative movement between the vehicle body and the wheel. A hybrid electromagnetic shock absorber where the magnets are directly driven by the wheel and the two layers of magnets are also designed to obtain the stronger electromechanical coupling [5]. According to the Faraday's law $U = Bl \cdot v$ where U is the voltage output, Bl is the electromechanical coupling constant and v is the speed of the moving conductor [6]. For the above-mentioned shock absorbers, the magnet speed with respect to the coils is limited to the relative speed between the vehicle body and wheel. The current output of the regenerative shock absorber also relies on the electromechanical coupling constant which is related to design of the combination of the coils and magnets. The large electromechanical coupling constant may bring a potential problem of large size and weight of the shock absorbers [7], which is against the sustainable nature of the regenerative shock absorber.

To further improve the performance of the regenerative shock absorber, many studies have focused on development of the amplifying mechanism to increase the magnet speed with respect to the coils without adding too much extra weight. Rack and pinion mechanisms [8,9], ball-screws [9–13] are widely used to convert the unidirectional reciprocating movement of the shock absorber into the rotational movement of a generator. Because of the use of the DC generator, the unidirectional reciprocating movement needs to be rectified into one directional rotation through one-way clutch [8]. The shock absorber can also be connected to the hydraulic system to achieve the motion conversion and the speed amplification. In such designs, check valves are utilized to produce one-way flow for the hydraulic motor which drives a DC generator, the rotating speed of which can then be amplified by adjusting the pipe profile [14]. Some innovative designs are also proposed that includes adding the secondary amplifying cylinder in the shock absorber to provide propulsion to a DC generator, which operates on a faster speed due to the smaller pipe line [15,16].

The regenerative shock absorbers with the amplifying mechanism often have a higher magnet speed with respect to the coils. In order to compare the regenerative shock absorbers with and without the amplifying mechanism, a linear generator and a rotary generator with ball screws have been incorporated respectively into two shock absorbers of an ATV (all-terrain vehicle) [17]. The result indicates that in terms of the power output, the rotary generator with the speed amplifying mechanism has more advantages over the linear generator directly driven by the oscillators. However, there is a lack of fairness as the generators used in the experiments have significantly different configurations, such difference can largely affect the energy generating ability and outcomes. Additionally, in order to generate unidirectional rotation to drive the DC generator, the mechanical motion rectifier such as one way clutches or check valves have to be incorporated, which potentially results in more mechanical energy loss due to the friction losses. Therefore, whether the speed amplifying mechanism is able to enhance the overall performance of the regenerative shock absorber is still unknown.

This paper presents the design and modeling of the double speed regenerative shock absorber (or double speed RSA) that utilizes the reciprocation of the electricity-generating coils for harvesting the vibrational energy. The double speed RSA is equipped with the rack and pinion mechanism to amplify the magnet speed with respect to the coils, therefore the induced current and voltage can be increased. The parameters of the double speed RSA and regenerative shock absorber without the double speed amplifying mechanism (or single speed RSA) have been identified through experimental measurements. Sinusoidal wave excitations and random signal excitations have been applied as the road profile excitation input to validate the simulation models in terms of voltage output, power output and efficiency. To further evaluate the responses of a vehicle to the random road profile displacement excitation input, the comparison based on the Monte Carlo simulation between the double speed RSA and single speed RSA have been conducted.

Furthermore, the evaluation of the double speed RSA can be extended to that of any regenerative shock absorber with the reciprocating coils by introducing two defining parameters: amplification factor n and the reciprocating coil mass m_c . The proposed work can then be optimized by tuning these two parameters in a reasonable range for the maximization of the power.

2. Conceptual design

The working principle of the double speed RSA is shown in Fig. 1. Two sets of rack and pinion mechanism are installed in between the magnets and coils to increase the magnet speed with respect to the coils for larger current and voltage induction while converting the kinetic energy into electricity. The magnets are connected to the wheel assembly and the rack and pinion mechanism is connected to the upper vehicle body. As a result, when going through the compression phase, the coil moves down and the magnets move up in the same speed and vice versa, as a result the magnet speed with respect to the coils is doubled.

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