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A novel indirect-drive regenerative shock absorber for energy harvesting and comparison with a conventional direct-drive regenerative shock absorber

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HIGHLIGHTS

- A novel regenerative shock absorber for motion conversion and energy harvesting.
- Simultaneous motion conversion, speed amplification and fluctuation elimination.
- An indirect and direct-drive system comparison for the same generator configuration.
- Parameter sensitivity analysis of the direct and indirect-drive systems via Monte-Carlo siulation.

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ABSTRACT

Energy harvesting from the shock absorbers is now becoming an important technology in developing the electrical vehicles. Compared with other kinetic energy sources such as engine and brake systems which are continuous or periodic, the shock absorber is subjected to the fluctuated linear motion with relatively small displacement. This paper presents a novel indirect-drive regenerative shock absorber system that utilizes an arm-teeth mechanism to achieve linear to rotary motion conversion and to amplify its input speed for increasing energy harvesting output. The fluctuation of road randomness can be smoothed out through the flywheel. The proposed design has the advance of achieving all the targets with less number of components. Two prototypes of the direct-drive and indirect-drive regenerative shock absorbers have been built. The simulation models have been developed and validated by experimental results. The performance of this new indirect-drive system has been compared, through experimental testing and analytical modeling, with that of a conventional direct-drive system of the same generator configuration. The results show that this indirect-drive system can achieve greater peak power output and broader frequency bandwidth than the conventional direct-drive system. The indirect-drive system also presents a better ride comfort up to 13 Hz. Using Monte Carlo simulation, a parameter sensitivity analysis of both the indirect-drive and direct-drive systems has been carried out to compare their energy harvesting performances in terms of increasing the peak power output and broadening the energy harvesting frequency bandwidth. In both the systems, choosing the right tyre stiffness and electromechanical coupling constant is beneficial to increasing the peak power output ratio and the harvesting frequency bandwidth. The right choice of the gear ratio can further improve the peak power output ratio of the indirect-drive system. The variation of these parameters will allow for possibility of achieving higher power output when vehicle is driven on random road surfaces.

1. Introduction

Improving energy efficiency of transport vehicles has attracted great interests in the past few decades due to the need to reduce consumption of the fossil fuel worldwide. Regenerative shock absorber is one of the promising technologies for reducing fuel consumptions that have been

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Nomenclature

$v_{coil\_magnets}$	coil speed with respect to the magnets
m_c	coil mass
R_i	coil resistance
L	coil inductance
P_{input}	damping power
F_{Wi}	damping force of the ith oscillator
η_{tp}	efficiency of top plate
η_{pg}	efficiency of planetary gear
η_g	efficiency of generator
m_s	equivalent reciprocating mass
c_L	equivalent suspension damping
Bl	electromechanical coupling
r	equivalent radius
P_E	electrical power
R_e	external resistance
$j\omega$	excitation frequency
i	gear ratio
r_g	generator rotor radius
$U_{generated}$	generated voltage
k_e	generator constant
ω_g	generator angular velocity
F_{Gi}	inertia force of the i^{th} oscillator
F_{LR}	Lorentz force
m_m	magnets mass
n	multiplication factor
m_p	planetary gear mass
r_P	planetary gear radius
m_2	quarter vehicle body mass
c_R	rotary damping coefficient
y	road excitation displacement amplitude
J_{FW}	rotational inertia of the flywheel
J_{am}	rotational inertia of the driving arm
J_{pcr}	rotational inertia of the planetary gear carrier
J_P	rotational inertia of the planetary gear
J_g	rotational inertia of the generator
J_s	rotational inertia of the sun gear
k_2	suspension stiffness
c_2	shock absorber damping
F_{Ki}	spring restoring force of the i^{th} oscillator
m_{tp}	top plate mass
$\eta_{direct\text{-}drive}$	total conversion efficiency of the direct-drive system
$\eta_{indirect\text{-}drive}$	total conversion efficiency of the indirect-drive system
k_1	tyre stiffness
c_1	tyre damping
m_1	wheel assembly mass

adopted in road transport vehicles. When a vehicle is driven on a road, the unevenness of the road surface causes the vehicle body to vibrate. A conventional hydraulic shock absorber in the vehicle's suspension system coverts the vibration kinetic energy into heat that is then dissipated into the ambient. By contrast, a regenerative shock absorber can convert the kinetic energy directly into electrical energy that can be stored in batteries or supercapacitors for later use. For a commercial vehicle, it is expected that the potential power of 45–420 W can be generated by one hydraulic regenerative shock absorber considering the standard driving pattern and the vehicle roll mode [1,2]. More energy can be harvested in the case of higher vehicle speed and rough terrain [3].

Among all the energy harvesters that can convert kinetic energy into electrical energy, the electromagnetic generator is most efficient considering the modal resonant frequency of the vehicle, travel displacement of the shock absorber and the size of the harvester [4,5]. For an electromagnetic generator, according to Faraday's law of induction in Eq. (1), higher voltage can be generated by increasing the electromechanical coupling constant *Bl* or the coil speed with respect to the magnets $v_{coil\_magnets}$.

$$U_{generated} = Bl\cdot v_{coil\_magnets} \tag{1}$$

Regenerative shock absorbers can be divided into two categories: direct-drive regenerative shock absorber and indirect-drive regenerative shock absorber. When a vehicle is driven over an uneven road, the displacement excitation due to the road unevenness or bumps will cause a relative motion between the sprung mass and the un-sprung mass. The direct-drive regenerative shock absorber has its coil and magnets directly connected to the sprung mass and un-sprung mass, respectively. As a result, the electrical energy is generated when there is relative movement between the coil and the magnets. One of the main advantages of direct-drive regenerative shock absorbers is their structural simplicity which renders it more durable and robust. For a given relative speed between the sprung mass and un-sprung mass, the harvested energy is directly related to the electromechanical coupling constant *Bl*, which is dependent of magnetic field intensity and coil profile. Many studies have focused on applying premium magnetic patterns to increase the magnetic field intensity [6–12]. Adopting two layers of magnets has been investigated in [9,10,13]. The use of the Halbach magnetic array, as another way to increase the magnetic field intensity, has also been studied in [11,12,14]. Regardless of magnetic field intensity, the coil profiles is another factor to increase the electromechanical coupling constant *Bl*. Tang et al. [10] proposed to have four phase coil to reduce the current cancellation. The number of coil layers, coil resistance and gauge numbers for the premium energy output have been investigated by Elvin et al. [15].

In an indirect-drive regenerative shock absorber, the relative reciprocating motion of the sprung and un-sprung masses is converted into a unidirectional rotational motion through mechanisms of the ball screw [16–22], rack-pinion system [23–25], rod-helical slot system [26], algebraic screw [27] and clutch. The rotational motion speed is then amplified through a gearbox which is connected to a rotational direct current (also called "DC") generator. Therefore the power output of the generator is increased due to the amplified speed, although more mechanical friction losses are introduced by the mechanical complication. The fluctuation of the rotational speed can be smoothed out by a flywheel to eliminate the acceleration force induced by the reciprocating motion [20,24,28]. Hydraulic regenerative shock absorber can also be regarded as indirect-drive regenerative shock absorber for its hydraulic motion rectifier and integrated hydraulic DC generator [29–33]. Similar to the mechanical indirect drive regenerative shock absorber, a better fluid motion conversion can be achieved through the complicated hydraulic mechanism, which however may result in more energy loss.

Despite of all the above-mentioned technologies, there is a lack of a direct comparison between the indirect-drive and direct-drive regenerative shock absorbers in terms of vibration energy harvesting. Zhang et al. [34] proposed a regenerative shock absorber with a double speed mechanism that can increase the shock absorber velocity for two times more than the conventional regenerative shock absorber. However the mechanism cannot achieve the motion conversion, as a result the system is more prone to failure due to the amount of dynamic load applied. Another interesting experiment was conducted by Gupta et al. [13] where the direct-drive and indirect-drive regenerative shock absorbers were installed on an all-terrain vehicle running over a beam. The direct-drive regenerative shock absorber has a linear electromagnetic generator with two layers of magnets for a larger electromechanical coupling constant *Bl* while the indirect-drive regenerative