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# Electro-hydraulic damper for energy harvesting suspension: Modeling, prototyping and experimental validation

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## HIGHLIGHTS

- A novel electro-hydraulic energy harvesting damper was proposed for off-road vehicles.
- Unidirectional generator rotation was realized to improve energy harvesting efficiency.
- Asymmetric rebound/compression damping force was obtained for better road-tire contact.
- Damping and regenerative characteristics were studied via simulation and test.
- Large controllable damping range is achieved as the basis to control active suspension.

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## ABSTRACT

This paper presents an electro-hydraulic semi-active damper to harvest the suspension kinetic energy for the purpose of further improving the fuel efficiency of off-road vehicles. This regenerative damper can transform the reciprocating suspension vibration into unidirectional generator rotation, and meanwhile achieve approximately asymmetric rebound/compression damping force in a wide controllable region. The working mechanism of this new damper is first elaborated, and then its dynamic model is mathematically derived based on the first-principle analysis of hydraulic and electric components. A prototyping damper is designed and manufactured, and a series of experimental tests are conducted to demonstrate its effectiveness to generate the damping characteristic and energy harvesting capability.



## 1. Introduction

Many studies on the low carbon vehicles have been focusing on how to reduce energy consumption as much as possible [1,2]. The most famous efforts in automotive industry include powertrain energy management [3] and braking-energy recovery [4]. The harvesting of suspension energy is a new trial, however, the main challenge is to reduce its influence on vehicle dynamical performances while reducing fuel usage [5]. In the daily usage of a ground vehicle, only 10–16% of fuel energy is used to drive the car to overcome the resistance from road friction and air drag [6]. One major loss is the dissipation of vibration energy by active and/or semi-active suspensions under the excitation of vehicle acceleration and road irregularity, especially for off-road vehicles.

For the off-road vehicles, such as military vehicles and SUVs, the energy harvesting suspension has more potential for the industry application [7]. Zuo et al. [8] suggest that road roughness, tire stiffness, and vehicle driving speed have great influences on the harvesting power potential, and for a middle-sized vehicle, 100–400 W average power is available in the suspensions at 60 mph on B and C class roads. The road tests conducted by Audi AG [9] show that the average recovery power is about 150 W when the passenger car is driven on German roads, 3 W on newly paved highways, and 613 W on the rugged country road. Moreover, the dampers for off-road vehicles need to frequently move fast and at a large stroke to be able to drive off the pavement, which leads to serious temperature-rise in damping oil. This temperature-rise severely affects the vehicle performance and accelerates the failure of damper components [10]. The damping oil temperature rises rapidly, which means that there is a considerable energy dissipation to the surrounding environment, and this dissipated energy also comes from the vehicle's engine power [11].

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The energy harvesting damper is the core of active and semi-active suspensions, which can be categorized into two types: electromagnetic and electro-hydraulic. The electromagnetic regenerative damper mainly contains two components: energy conversion (linear or rotary electric generators) and transmission (from reciprocation to rotation) devices.

The transmission device is used to transmit the reciprocating suspension vibration into rotation for easier energy conversion. The key techniques of transmission device include ball screw, rack-pinion, hydraulic transformation system and link mechanism, etc. Zuo and Scully design a retrofit regenerative damper for compact space deployment, in which a four-phase linear generator with high permeable magnetic loops is used to directly harvest reciprocating vibration [12]. The general layout of linear motor electromagnetic regenerative damper is shown in Fig. 1(a).

Song et al. patented a regenerative suspension system based on the rotary electromagnetic motor and ball screw mechanism, which can switch between passive mode and semi-active mode [13]. Kawamoto et al. [14] and Singal et al. [15] analyzed the relationship between suspension damping performance and energy consumption of this kind of regenerative suspension, and achieved zero-energy semi-active damping adjustment via Skyhook adaptive control algorithm. The simplest layout of such electromagnetic regenerative damper is shown in Fig. 1(b). Li and Zuo [16,17] designed a regenerative damper based on the rotary electromagnetic motor and rack-pinion mechanism, which can switch reciprocating suspension vibration movement into unidirectional generator rotation via a mechanical motion rectifier (MMR), and adjust the suspension damping coefficient by changing external load connected with the generator. The prototype test results show that the power regenerative efficiency of this regenerative damper can reach to 60% under high frequency excitation. Zhang et al. [18] proposed a novel high-efficiency energy regenerative damper using rack-pinion mechanism and supercapacitors, and then this damper is applied to extend the battery endurance of an electric vehicle (EV). The general layout of rack-pinion regenerative damper is shown in Fig. 1(c).

Self-powered system design combined with electrorheological (ER) or magnetorheological (MR) dampers is another hot topic. Choi et al. [19] set a rack-pinion mechanism outside of the outer cylinder of an ER damper, which can change the linear reciprocating vibration into generator rotation, and then the power outputted from the generator can be used as power supply for the sensing system of ER suspension. Sapinski [20,21] paralleled an electromagnetic induction device (EMI) with a MR damper, and the EMI harvests suspension vibration into electricity which can be used to power the control and sensor system of the MR suspension.

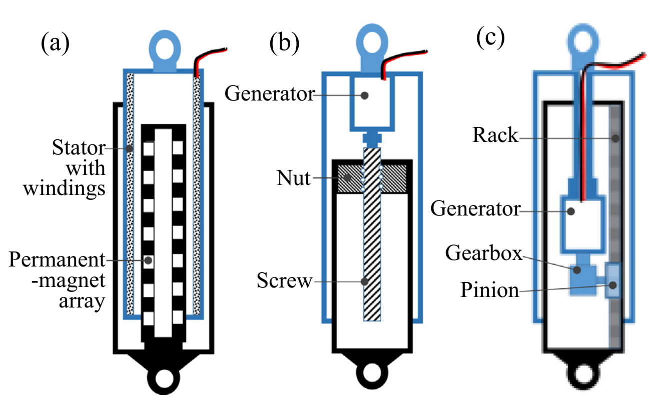


**Fig. 1.** The general layout of different electromagnetic regenerative dampers. (a) Linear motor, (b) ball screw, and (c) rack-pinion.

The electro-hydraulic regenerative damper also has many different layouts. Stansbury et al. [22] disclosed an electro-hydraulic regenerative damper, whose hydraulic circuit can switch reciprocating piston vibration into hydraulic energy, and then drive the hydraulic motor and generator to rotate, in order to convert the hydraulic energy into electricity. Due to the randomness of the uneven road excitation, the oil flow direction will be switched frequently, which not only reduces the working reliability of the system, but also greatly decreases the energy efficiency of the generator.

Guo et al. designed a pumping electro-hydraulic regenerative damper [23] and an interconnected active regenerative suspension system [24]. After analyzing the relationship between regenerative damper and vehicle fuel efficiency [25], the results show that the off-road vehicles and heavy trucks have more potential to improve the fuel economy via the regenerative damper.

Electromagnetic regenerative damper has a relative low load carrying capacity, therefore it is more suitable for minivans and passenger cars etc. Electro-hydraulic damper can provide a higher damping force which is usually required by off-road vehicles. Therefore, it is more practical to study the electro-hydraulic energy harvesting suspension for off-road vehicles, heavy trucks, mining vehicles, military vehicles and engineering vehicles, which have large weight and poor road conditions.

This paper presents an electro-hydraulic energy harvesting damper, which has following advantages: (1) transform the reciprocating shift of the suspension vibration into unidirectional generator rotation which can improve energy converting efficiency, (2) realize approximately asymmetry rebound/compression damping force which is useful to improve vehicle handling, and (3) achieve relatively large controllable range of damping force to make it possible to be used in active/semi-active suspension.

The rest of this paper is organized as follows: In Section 2, an electro-hydraulic energy harvesting damper design is proposed and its mathematical model is introduced. The prototype design and test setup are given in Section 3. Simulation and experimental verification results and discussions of the oil temperature-rise, passive damping, damping force controllable and regenerative characteristics are given in Section 4. This is followed by the concluding remarks and future issues in the final section.

## 2. Damper design and modeling

Based on the analysis and summary of existing energy harvesting suspension systems, their general configuration is illustrated in Fig. 2. The actuator and energy harvesting module (can be collectively referred as regenerative damper) are the core parts of this kind of suspension system, which can transform suspension reciprocating mechanical vibration into recoverable electricity. Due to the random road excitation, the output voltage of above regenerative damper usually fluctuates in a wide range. The charge management module in Fig. 2 is used to narrow the range of fluctuating voltage, thus efficiently charging the battery pack. By collecting the suspension feedback signals, the controller can regulate the charge management module in real time, and improve the ride comfort and fuel efficiency.

### 2.1. Design

Three pumping electro-hydraulic regenerative dampers (e.g., mono-tube [23], twin-tube [24] and integrated mono-tube [26]) were designed. Each of them has its own advantages and disadvantages, and is applicable to different vehicle requirements and installation conditions. However, they share similar design requirements: (1) improve the generator efficiency and reliability