A Review on Energy-Regenerative Suspension Systems for Vehicles

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***Abstract*—The conventional vehicle suspension dissipates the mechanical vibration energy in the form of heat which waste considerable energy. The regenerative suspensions have attracted much attention in recent years for the improvement of vibration attenuating performance as well as the reduction of energy dissipation. Above all, the amount of energy dissipation and the potential of energy regeneration are discussed, then the research and development of regenerative suspension is reviewed, and the energy harvesting schemes and their characteristics are summarized and remarked. In conclusion, only combining vibration reducing performance and energy harvesting efficiency can the regenerative suspensions have a promising prospect.**

***Index Terms*—vehicle suspension, energy regeneration, electromagnetic actuator, green manufacture**

I. INTRODUCTION

THE function of vehicle suspension system is to support the weight of vehicle body, to isolate the vehicle chassis from road disturbances, and to enable the wheels to hold the road surface. Two chief elements in suspension are spring and damper. Conventionally, damper is designed to dissipate vibration energy into heat to attenuate the vibration which is transmitted from road excitation. However, the dissipated heat is from fuel or electrical power. It is a pity that so much energy is wasted.

Green manufacturing, also called environmentally conscious manufacturing, is one of the most popular topics nowadays. The future of green manufacturing technology is foreseeable, especially on vehicle industry. Since the suspension is an important source of energy dissipation, it is feasible to harvest its vibration energy and convert into regenerative energy to improve the vehicle fuel efficiency. Therefore, so called regenerative suspensions arise as the times require. Instead of dissipating the vibration energy into heat wastes, the damper in regenerative suspension will transform the kinetic energy into electricity or other potential energy and store it for late use. The stored energy can be used to tune the damping force of the damper to improve the suspension performance or to power vehicle electronics to increase vehicle fuel efficiency.

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II. ENERGY DISSIPATION OF VEHICLE SUSPENSION

In the past, we pay little attention to energy loss of vehicle suspension. However, how much energy is dissipated by the shock absorbers of vehicle suspension? According to reference [1], only 10-20% the fuel energy is used for vehicle mobility. One of the important losses is the energy dissipation in suspension vibration. Velinsky *et al*. [2] concluded that the dissipated energy by suspension dampers is related with road roughness, vehicle speed, suspension stiff and damping coefficient. Segel *et al*. [3] analyzed the energy dissipation of dampers of passenger vehicle, and shown that the total power of four dampers was about 200W when running on a poor road at the speed of 13.4m/s. These data indicate that the energy dissipation of vehicle suspension can't be ignored.

III. ENERGY HARVEST FROM VEHICLE SUSPENSION

On the other hand, how much energy we may capture from vehicle suspension? Suda *et al*. [4] proved that the harvested energy in the regeneration process is enough to meet the energy requirement in consumption process for electromagnetic active suspension, which means the suspension is self-powered. The estimation by H su [5] indicated the average regenerative power of each suspension for GM Impact running on the highway at 16 m/s reached 100W accounting for about 5% of driving power. F. Yu *et al.* [6] compared the energy consumption of passive and active suspension of car. Their simulation, under the conditions that the vehicle speed was 20m/s, the road roughness was class C, the simulation time was 20s, indicated that energy consumption of passive suspension is 651 kJ, while 645 kJ for active suspension which decreased the RMS of sprung mass acceleration by 50%. If the suspension vibration energy can be recycled, the energy consumption of active suspension will be reduced significantly. Theoretical results show a maximum of 10 % fuel efficiency can be recovered from vehicle suspension system by implementing regenerative shock absorbers [1].

IV. CONFIGURATION OF REGENEREATIVE SUSPENSIONS

According to the working principle, the regenerative suspension can be divided into two types: mechanical and electromagnetic regenerative suspension.

A. *Mechanical Regenerative Suspensions*

The mechanical regenerative suspension is reformed from

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the traditional hydraulic/ pneumatic suspension. It absorbs the kinetic energy of suspension and converts into potential hydraulic / pneumatic energy to be stored in accumulator. However, these hydraulic / pneumatic systems characterize some disadvantages. One, the complex pipeline system has considerable weight and need more installation room. Two, hose leaks and ruptures may disable the whole system. Three, the responding bandwidth of hydraulic / pneumatic systems is narrow, which confines the suspension performance. Four, the reuse of the regenerated hydraulic / pneumatic energy are limited, especially when the automotive industry is toward commercializing hybrid electric vehicles and full electric vehicles. Hence, the researches on hydraulic / pneumatic regenerative suspension are relative rare. Jolly *et al.* [7] proposed an energy regenerative system based on hydraulic device to control the vertical vibration of vehicle seat using the regenerated energy. Nissan [8] developed a fully active suspension system with hydraulic actuators, which suppresses the suspension vibration by accumulating or releasing the energy in the accumulator under the control of valves. Noritsugu [9] investigated an active air suspension via reclaiming the exhaust to control suspension vibration for improving suspension performance and decreasing energy consumption.

B. *Electromagnetic Regenerative Suspensions*

On the contrary, electromagnetic regenerative suspension transforms the shock energy into electric energy that is more convenient to store and reuse, and has high performance, increased efficiency, less space requirements, and so on [10]. In recent years, electromagnetic suspension (EMS) system has drawn worldwide attention. Permanent magnets motor is favored in EMS to provide active force in actuator mode or damping force in generator mode. The damping force can be simply changed by tuning the shunt resistances. There are six types of electromagnetic regenerative suspension classified by structure configuration, and relating researches will be stated as follow.

Direct-Drive Electromagnetic Suspension

In direct-drive electromagnetic suspension, linear permanent magnets motor is usually used to replace the traditional shock absorber. It turns the mechanical energy of relatively motion between vehicle chassis and wheel into electric energy needing no transmission devices.

Design theories of the linear motor may reference [11-12]. Okada *et al.* [13] studied the active and regenerative vibration control suspension using linear actuator, and its performances of vibration isolation and energy regeneration were analyzed. Suda *et al.* [14] investigated a self-powered active vibration control system with two linear motors for truck cabins. In this system, an electric generator that is installed in the suspension of the chassis regenerates vibration energy and stores it in the condenser. An actuator in the cab suspension achieves active vibration control using the energy stored in the condenser. Since the weight of the chassis of a typical heavy duty truck is greater than that of the cabin, vibration energy in suspension of a chassis is expected to be greater than that in the cab suspension. So this system is self-powered. Further more, they proposed self-powered active vibration control using a single electric actuator [15]. Goldner [16] invented an electromagnetic linear generator to capture the suspension vibration energy. Zuo *et al.* [17] designed a linear energy harvester to test the amount of energy which can be regenerated. Gysen *et al.* [10] utilized direct-drive electromagnetic motor to improve the suspension performance, and proved its efficiency for harvesting vibration energy. Bose Company [18] applied the linear motor in vehicle suspension, shown as Fig.1. The system ends up consuming one-third of the energy used by a car's air conditioner.

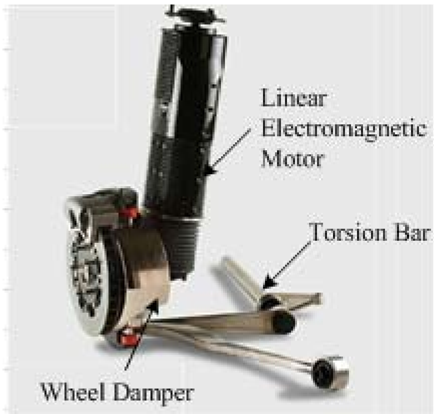

Fig.1 Electromagnetic suspension developed by bose

Ball Screw Electromagnetic Suspension

Ball screw is a common transmission device that converts linear motion into rotation. Arsem [19] invented an electric shock absorber with ball screw to harvest vibration energy. Murty [20] also invented a ball screw electric damper whose damping force can be adjusted by changing the shunt resistance. Suda *et al.* [21] proposed a ball screw harvester (shown as Fig.2), and analyzed its dynamic and regenerative characteristics. F. Yu *et al.* [22] designed a ball screw damper and verified its performance.

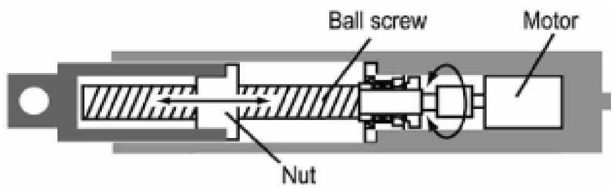

Fig.2 Ball screw harvester

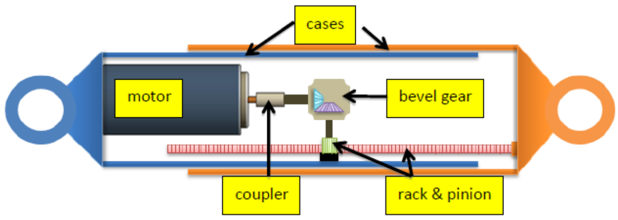

Fig.3 Rack-pinion electromagnetic damper

Rack-Pinion Electromagnetic Suspension

Rack-pinion can also convert linear motion into rotation. Suda *et al.* [23] studied a regenerative active suspension combining rack-pinion and rotary motor. Beno *et al.* [24-25] developed electronically controlled active suspension system (ECASS), which adopted the rack-pinion configuration. The experiment results indicated that the limit speed and handling performance of vehicle had been enhanced significantly. Pei [1] designed a rack-pinion damper incorporating a bevel gear for changing the motor axes to parallel with the orient of

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linear motion, shown as Fig.3.

Planetary Gear Electromagnetic Suspension

Planetary gear is always used to reduce or increase rotate speed. Introducing the planetary gear is helpful for boosting motor efficiency and active force. For example, in order to improve the regenerative efficiency, Suda *et al.* [26-27] add a planetary gear to ball screw damper. Horstman incorporating with L-3 and Texas University is developing ECASS for tracked combat vehicle. All the elements including motor, planetary gear set, sensors, are integrated in road arm, shown as Fig.4. This system has a sufficient active force, compact structure and good safety property that the combat vehicles require.

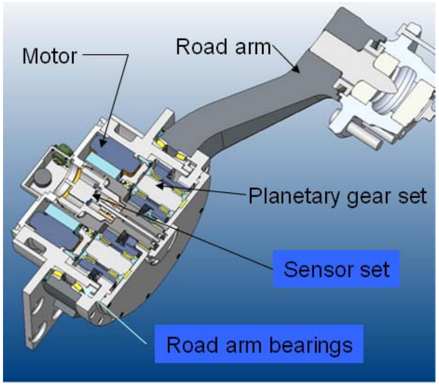

Fig.4 Actuator for combat vehicle suspension

Hydraulic Transmission Electromagnetic Suspension

Levant Power Corp. [28] is developing a regenerative damper, called GenShock, combining hydraulic transmission and electric motor. Fig.5 shows the working principle of this damper. A suit of rectifying pipe guarantees that the hydraulic motor driven by fluid rotates by a consistent direction whatever the piston runs up or down. Because the rotation direction of electric motor doesn't alternate frequently, the regenerative efficiency is enhanced obviously.

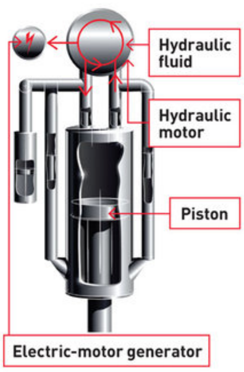

Fig.5 Hydraulic transmission regenerative damper

Levant Power Corp. claims that GenShock increasing fuel economy of by up to 6% for military vehicles as well as improves ride quality via an adaptable, variable-damping suspension. On the other hand , reduced heat dissipation in the damper through energy recovery helps diminish maintenance requirements. Xu *et al.* [29-30] proposed a hydraulic transmission electromagnetic energy-regenerative suspension, introduced its working principle, and the simulation results revealed that its comprehensive performance is superior to that of the passive suspension.

Self-Powered Magnetorheological Suspension

In recent decade, magnetorheological (MR) damper has been shown a cheerful prospect for structural vibration reduction, because of its mechanical simplicity, high dynamic range, low power requirements, large force capacity and robustness. Aims to save energy further more, many scholars have been studying self-powered MR damper. Jung *et al.* [31] proposed a self-powered smart damping system that consists of an MR damper and an electromagnetic induction (EMI) device to reduce vibrations of stay cable. The EMI device absorbs vibration energy to generate electrical energy and power the MR damper. Though the EMI device is separated from the MR damper, it provides a new technology scheme for self-powered vibration control system. Choi [32] and Bogdan [33] exerted some similar researches. Chen *et al.* [34] proposed a self-sensing MR damper with power generation, shown as Fig.6. In this structure, MR damper and power generator is integrated into an organic whole and the voltages of contiguous coils with different phase are utilized to calculate the relative velocity.

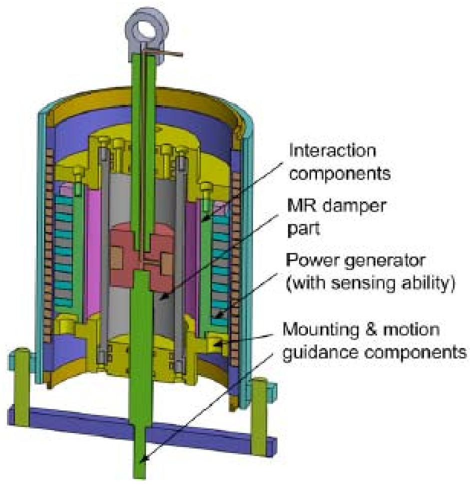

Fig.6. Self-sensing MR damper with power generation

V. REMARKS

A. Conflict

The primary purpose of improving suspension performance is to better ride comfort and handling stability, such as active suspension, semi-active suspension. Active suspension owns the best vibration control performance, but must consume lots of energy, while the actuator just works as passive or semi-active damper in regeneration process, whose control performance is not excellent as that of active state. So as to saving energy, despite some strategies may be established to reach the balance between regenerated and consumed energies, we have to scarify vibration control performance evidently. Thereby, there is conflict between regeneration and vibration control [34].

B. Efficiency

For regenerative suspension, how to enhance the efficiency of harvesting energy is very important. For absence of speed increaser, the direct-drive motor has a low energy recovering efficiency. However, as to ball screw and rack-pinion damper, speed increaser leads to more inertia loss which decreases the regeneration efficiency and

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suspension performance. In comparison, the hydraulic transmission regenerative damper shows obvious advantage in term of regeneration efficiency since it is expedient to equip speed increaser and there is no inertia loss resulting from alternating the rotation direction frequently.

C. Reliability

Reliability is a key factor for engineering application. Direct-drive motor has a high reliability for itself, but any faults in circuit will result in disappearance of damping force, which doesn't accord with the fail-safe principle. For ball screw and rack-pinion harvester, bump excitations or alternating rotation directions frequently will result in damage of harvester. Hydraulic transmission and self-powered MR damper have a high reliability.

VI. CONCLUSION

Conventionally, the vibration energy of vehicle suspension is dissipated as heat by shock absorber, which wastes a considerable number of resources. Regenerative suspensions bring hope for recycling the wasted energy. All types of regenerative suspension, especially electromagnetic suspension, and their properties are reviewed in this paper. From the perspective of comprehensive performance including vibration control ability, regenerative efficiency and application reliability, the configuration of hydraulic transmission and self-powered MR damper shows the best attraction. With improvement of technology, regenerative suspension may become one of promising trends of vehicle industry.

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