Review on the Research of Regenerative Shock Absorber

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Review on the Research of Regenerative Shock Absorber

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***Abstract*—The regenerative shock absorber has become more attractive to several researchers and industries in the past decade. Due to the roughness of the road surface, vibration has been provided between the road surface and car body when drives on irregular road surface. The function of regenerative shock absorber is to recover the vibration energy which can be dissipated in the form of heat as waste. This paper first introduces the existing research and significance of regenerative shock absorbers and reviews the potential of automotive vibration energy recovery techniques, and then emphatically classifies and summarises the general classifications of regenerative shock absorber. Finally, it analyses the modeling approaches of shock absorbers, actuators and dampers. With the increasingly prominent energy issues, regenerative shock absorber becomes one of promising trends of vehicles.**

Keywords-regenerative shock absorber; vibration energy; recovery potential; structure; modeling method.

I. INTROUDUCTION

With the sustained and rapid development of China's economy and society, vehicles have been popularized by millions of households as convenient personal transportation. To the end of 2017, the number of China's civil vehicles reached 217 million (an increase of 11.8% from the end of the previous year), of which private cars were about 186 million (an increase of 12.9%) [1]. However, the explosion of vehicles has also led to huge energy consumption, serious waste, and a series of problems such as environmental pollution. For commercial cars, only 10% to 16% of the fuel energy has been used to propel the driving. Most of the energy is wasted on road friction and thermal exhaust. Among them, the kinetic energy loss by shock absorber is the main energy dissipation [2]. In order to deal with the increase of energy and environmental problems, the Chinese government has put forward the idea of green energy development and raised energy and environmental issues on the agenda. As an important part of China's industry, research on the energy recovery technology of vehicles is significant for the improvement of the energy efficiency.

During the driving process of a car, due to the excitation of the road, relative movement between the wheel and the car body will occur. This kind of movement is not conducive to the stability of the car and reduces the comfort of the passengers. A shock absorber is a device for applying the damping of the vibration between the wheel and the car body to improve the comfort and road handling of the vehicle, which is installed inside the suspension system with coil spring used in most vehicles. When the frame and the axle are reciprocally moved and produced relative displacement, the piston valve in the shock absorber also reciprocates within the cylinder, and the hydraulic oil in the cap-end and rod-end chambers of the shock absorbers or dampers repeatedly flow in the cylinder through the piston valve orifices [3]. The traditional automobile shock absorber converts kinematic energy into heat energy, and dissipates it into the air. In order to achieve the purpose of vibration reduction and good ride comfort. The energy can be recovered and reused whilst reducing the energy consumption and improve the endurance of vehicles, thus to achieve the purpose of energy conversion and emission reduction.

This paper reviews the background of research on regenerative shock absorber, and studies the vibration energy recovery potential of automobile vehicles. Then, the structures of the regenerative shock absorber are summarised and classified and some other approaches of modelling and simulating are introduced for follow-up work.

II. RESEARCH ON RECOVERY POTENTIAL OF AUTOMOBILE VEHICLE VIBRATION ENERG

In the past 30 years, many researchers have made relevant studies on the energy harvesting techniques of the suspension system. This section introduces the research status of the potential of energy recovery in automotive suspensions.

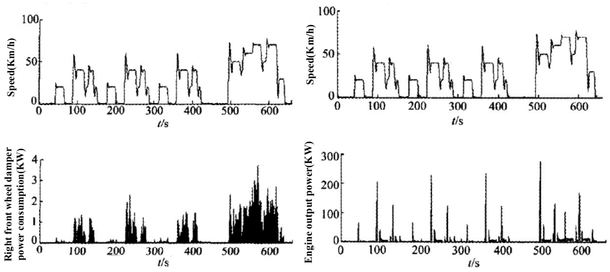
In 1982, SegeL [4] analysed the influence of the road surface act on the vehicle's driving resistance when the car is driving on road. The research results show that the energy dissipation of the suspension is related to road roughness and vehicle speed. In addition, the paper also discusses the additional resistance on the motion due to the sliding of a motor vehicle. It can been found that the actual fuel consumption of a motor vehicle is greater than the estimation of the laboratory measurements. From this point of view, the impact of road surface, tires, and suspension damping on the vehicle's running resistance has been investigated. It is concluded that when the car is driven at a speed of 48 km/h, the suspension system dissipates approximately 200 W of energy for 4 wheels.

In 1986, Browne [5] studied the energy dissipation in automotive shock absorbers of a running vehicle on urban road. It is found that each hydraulic shock absorber dissipates about 40-60 Watts.

In 1996, Hsu [6] discussed the application of electric motors which were used as the main actuators of active suspension systems for road vehicles. The authors focus on the capability of the energy harvesting on suspension system using a quarter-car model applied with linear quadratic optimal control, and determining potential recoverable power in terms of power spectral density analysis and computer simulation. The results show that the active system on a midsize car can recover about 100W of power per wheel on motorway, approximately 400W of energy can be recovered at the speeds of 96km/h.

In 2007, Kawamoto [7] and others presented a modelling of the electromagnetic damper (EMD) for automobile suspension. The validation of the model is demonstrated by comparing the numerical results with the experimental results that when a car is driven on a Class C road at a speed of 80km/h, each damper can recover 15.3W of energy.

In 2009, Yu [8] applied CARSIM simulation software to simulate the vehicle and completed the energy consumption calculation of the suspension system when the vehicle is driving on different road conditions at variable driving speeds. It summarises that when the car is running at the speed of 10m/s in the class C road, the energy dissipation of the suspension accounts for 42.3% of the input power of the engine.



(a)Speed-damper energy consumption (b)Speed-engine input power

Figure 1. The Simulation Results of Car Driving

In 2010, Yu [9-10] simulated and analysed the performance of a car. When the car is driven by a speed of 72km/h on the Class C road, it is found that the energy dissipated by the suspension is about 651 kJ.

In 2013, Zhang [11] built a dynamic simulation model of the suspension system to test the average recoverable energy. When the vehicle speed is 30km/h at the Class A, B, C, D, and E roads, the recoverable power is 2.08 W, 8.33 W, 33.34 W, 133.37 W, and 533.21 W, respectively. According to the Class of the road surface is getting worse, it is clear that the recoverable energy increased with more incident excitation from the roughness of the road.

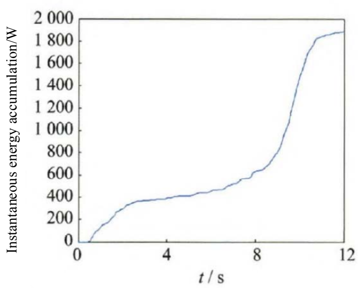


Figure 2. Accumulation of Recoverable Energy over Time

The energy dissipation of an automotive vehicle is highly related to the class of the road, the speed of travel, and the weight of the vehicle, which can aggravate the vibration of the vehicle. It means that when the speed and weight of vehicles are high, the recovery potential of vehicle vibration energy will also large.

III. RESEARCH ON STRUCTURE OF REGENERATIVE SHOCK ABSORBER

According to the discovery of the enormous potential for vibration energy recovery in automotive vehicles, researchers put more interested in the study of automotive regenerative shock absorbers. The section mainly introduces the different structures of regenerative shock absorber.

In 1990, Nissan Corporation [12] developed a hydraulic active suspension using oil pumps as its power source to produce pressure to negate the external forces of the vehicle. The suspension system can control the movement freely and continuously. Meanwhile, it also can improve the ride comfort and the ease of road handling. The actuator of the suspension system is composed of a hydraulic cylinder, an accumulator and a damping valve. The left hydraulic cylinder of the vehicle body is connected with the right side to form two independent hydraulic circuits. The suspension system is considered as the prototype of a hydroelectric energy absorber.

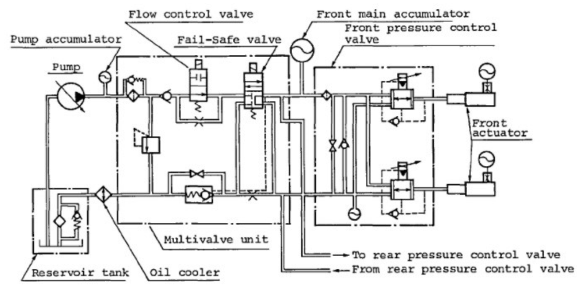
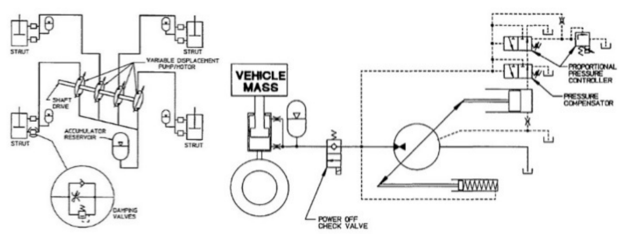


Figure3. Hydraulic Circuit Diagram of Nissan Suspension System

In 1991, Wendel [13] proposed a regenerative active suspension system. The system uses four independent and variable displacement pumps connected to the same shaft to drive independent suspension units. The initial study is focus on the capability of energy recovery. Additionally, the system integrates the corresponding power-saving features and control strategies.



(a) The regenerative pump (b) Hydraulic control system

Figure4. Regenerative Active Suspension System of Wendel

In 1992, Fodor [14] designed a linear transmitter. The proposed device is analysed as a damper in a typical passenger vehicle. The results show that the control scheme is feasible, and it can provide almost the same damping as the passive viscous damper while storing the damping energy.

In 1996, Okada [15-16] proposed a regenerative suspension shock absorber system. It is mainly used for active dampers to reduce energy dissipation without loss of damping efficiency. The shock absorber uses an electric actuator that can generate power at high speeds. In 2005, Okada [17] introduced active vibration control into a regenerative suspension damper designed to increase the damping capacity. The design applies to a mobile-mass shock absorber that uses PWM choppers to solve the dead-zone problem. However, the energy regeneration and active control modes cannot operate simultaneously. In 2008, Okada [18] improved the energy regenerative suspension, using electric actuators to regenerate power during high-speed motion. The results show that the system can provide better dynamics than the passive suspension system, and also can recover vibration energy.

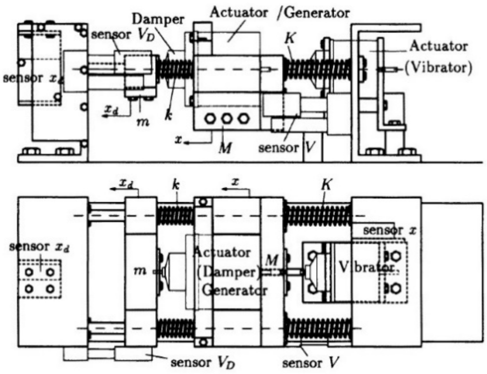
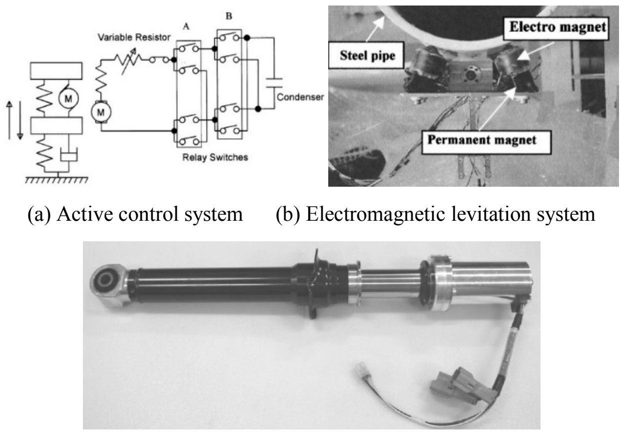


Figure 5. Regeneration Suspension System of Okada

In 1996, Suda [19-20] proposed a hybrid control system with active control and energy regeneration. for conventional passive suspension system. The damper converts vibration energy into thermal energy to consume vibrational energy. On the other hand, active suspension systems have better vibration isolation but it consumes extra energy. Therefore, the author uses a method to investigate the trade-off between vibration isolation and energy consumption in control systems: in a passive suspension system, an energy regeneration damper system that converts vibration energy into useful energy. The hybrid system combines with energy regeneration unit which includes the active control to obtain desirable vibration damping performance with energy consumption. In 1999, Nakano and Suda [21] applied the active vibration control method of regenerative vibration energy to realise the self-powered active control of heavy truck cab suspension. In this system, a generator is mounted to a chassis suspension to recover vibration energy and store energy in a condenser. Actuators in the cab suspension is used as an energy storage in the condenser for active vibration control. In 2000, Nakano and Suda [22] used a computer-controlled variable resistor to control the output force of the actuator. In the experimental study, self-powered active control is implemented and its isolation performance is evaluated. It proves that the self-powered active control can reach better isolation performance than that in semi-active and passive control systems. In 2002, Nakano and Suda [23] proposed a self-powered active control system recover energy from an energy regeneration damper to achieve active vibration control. It does not require external power supply. In this study, the anti-rolling system consists of an electric motor, so the motor is regarded as both energy regeneration damper and actuator. In 2003, Nakano and Suda [24] proposed a method to estimate regenerative energy and energy consumption using the dynamic characteristics of the system, including the gain of the active controller, the specifications of the actuator and the interference of the power spectral density in active control. From 2004 to 2007, Suda [7,25-27] designed a regenerative suspension system named electromagnetic suspension system (EMS). The system can automatically tilt according to the centrifugal force to reduce the power consumption of the control system. The vehicle EMD is also used to improve the stability and comfort of the vehicle.



(a) Active control system (b) Electromagnetic levitation system

(c) Shock absorber prototype

Figure 6. Energy Suspension Damper System of Suda

In 1999, Jolly [28] studied the potential of energy regeneration in vibration control systems. Such control systems hold the possibility of self-sustainability by alternately extracting and releasing energy originating from the vibrating system in a controlled non-passive manner. It is believed that the average energy flowing into the control system must exceed the outflow, and theoretically, no external power is required. The paper also proposed two applications of regenerative shock absorber which were named as base-excited suspension and periodically excited compound mounts, but the results were not as expected.

In 1999, Martins [29] studied an electromagnetic linear actuator to replace the existing active suspension. The solution has great potential to generate more regenerated energy from designed suspension system. Although the cost of electromagnetic actuators are very high. According to the result of material limitations, a hybrid suspension system is proposed. It combines the simplicity of a passive damper using with an electromagnetic active actuator in parallel. When a passive damper is in use, a smaller electromagnetic actuator can provide enough capability to the active suspension system to the level of performance it need.

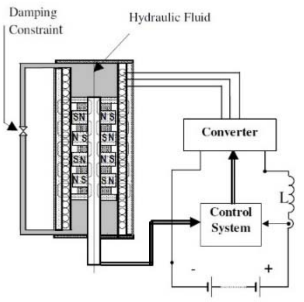


Figure7. Hydraulic Active-Passive Electromagnetic Suspension System

In 2003, Ding Y [30] proposed a method using two-degree-of-freedom (2-DOF) control. It attempts to control a multi-axis electrodynamics vibration system without applying iterative control. The article first introduces an ideal mathematical model and an uncertain weighting function for the system which uses a synthetic design feedback controller to form a 2DOF controller. Then, when the control performance still cannot be satisfied, an adaptive filter is added, and finally the performance of the controller is demonstrated through experiments using resonant samples.

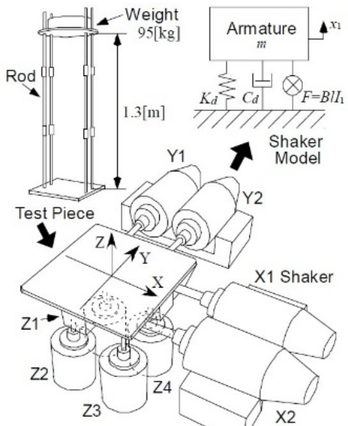


Figure 8. Two DOF controller and test system

In 2005, Bose Corporation [31] developed an electromagnetic active suspension system. The system uses Speaker technology to provide smoother driving. The system is equipped with a linear electromagnetic motor for each wheel. The algorithm manages the vehicle as a whole to prevent the body from rolling when steering and prevent the vehicle from leaning forward when the vehicle is stopped. The company uses its experience of driving the Bose loudspeaker voice coil to drive the linear motor. it can not only achieve the reduction of vibration, but also recover a small amount of energy for reuse.

Figure 9. Electromagnetic Suspension System of Bose

In 2009, the Massachusetts Institute of Technology (MIT) [32] developed a hydraulic liquid-electric regenerative shock absorber named GenShock. The shock absorber uses a mechanical-electric coupling method to generate the mechanical energy which is converted into electricity to supply additional equipment in the car. Afterwards, the research team established Levent Power, which was tested on a military Hummer. It is worth to mention that the shock absorber can recover up to 1 kW of electrical energy. The system integrates the hydraulic motor and the generator directly on the hydraulic cylinder which is ready to put on the market of the commercial vehicles.

Figure 10. GenShock Shock Absorber

In 2011, Singal [43] explored a new type of active suspension system. It combines the advantages of active and semi-active systems. This system can achieve active control to recover energy. Although the system is capable of recovering energy at high frequency excitations, additional energy is required to ensure vehicle smoothness at low frequency excitations (below 8 Hz).

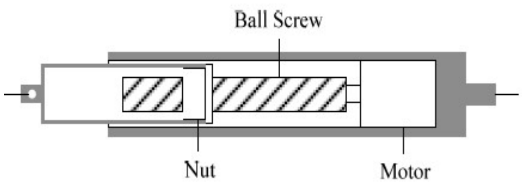
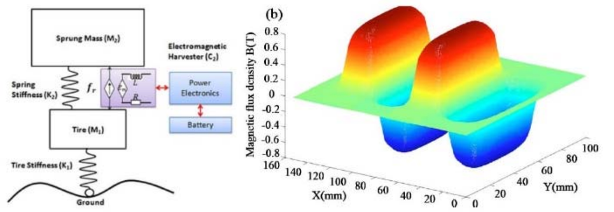


Figure 11. Energy Recovery System

From 2010 to 2013, Zuo L [33-42] conducted research on regenerative shock absorbers. In 2010, the team modified a regenerative damper using a rare-earth permanent magnets and high permeable magnetic loops to configure a four-phase linear generator. It can increase efficiency and reduce the weight of shock absorber itself. When the testing speed is from 0.25 to 0.5 m/s, it recovers 16-64W of energy eventually. In 2011, they proposed a new configuration of eddy current damper. This type of damper has high efficiency and compactness. It divides the magnetic field into multiple ones to reduce the resistance of the eddy current circuit and increase the damping coefficient. In 2012, a dual mass recovery device was proposed. The vibration energy recovery device is usually composed of a spring system in which an electromagnetic or piezoelectric transformer is connected in parallel with the spring. Tests show that the dual-mass vibration energy harvester can obtain more power. Under the random excitation of white noise, the collected power of the vehicle suspension is only proportional to the tire stiffness and the vertical excitation of the road. In the same year, the team proposed and studied a new piezoelectric energy harvester with multi-mode dynamic magnifier. It can significantly increase the bandwidth and energy collected from the ambient vibration. The design includes a multi-mode intermediate beam with a tip mass called a "dynamic magnifier" and an "energy collection beam" with a tip quality. The test results show that in the frequency range 3-300Hz, the recovery capacity is 25.5 times higher than that of the conventional cantilever type harvester. In 2013, the team conducted a comprehensive assessment of the energy. It can be used for recycling in vehicle suspension systems and analysing energy collection, ride comfort and roads. The results of the study show that road roughness, tire stiffness, vehicle speed, suspension stiffness, damper damping and vehicle mass have a great influence on the device recovery capacity. At the average speed of 60 miles per hour, medium-sized vehicles can recover 100-400W of power.



(a) Suspension system (b) Damper magnetic energy flow density

(c) Linear motor type energy absorber (d) Actual vehicle test

Figure 12. Research results of Zuo L

In 2015, Arif [83] designed an electromagnetic shock absorber for passenger car. Controllers are designed for energy regeneration and comfort based quarter car model. Shock absorber is designed and prototyped to absorb vibration energy and dissipate the energy as control actuation. The shock absorber uses DC permanent magnet motor to absorb and dissipate power.

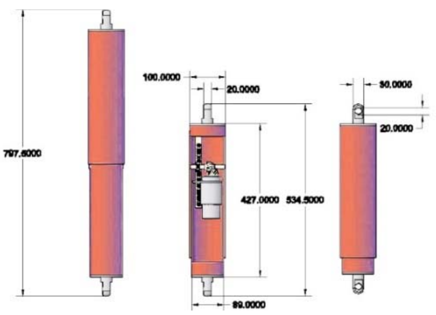


Figure 13. Prototype Dimension

In 2016, Dipesh [84] designed a kind of regenerative shock absorber. The shock absorber is installed between chassis and wheels to suppress the vibration, mainly induced by road roughness. As shown in Fig.14, the piston produces linear motion in big cylinder and the linear motion rectify in second cylinder by volume difference in two cylinders. So, the second cylinder have large linear motion compare to the first one. This linear motion of second cylinder converts into rotary motion by rack and pinion gears. Suitable size generator is attached with the pinion gear, which rotate and convert kinetic energy into electrical energy.

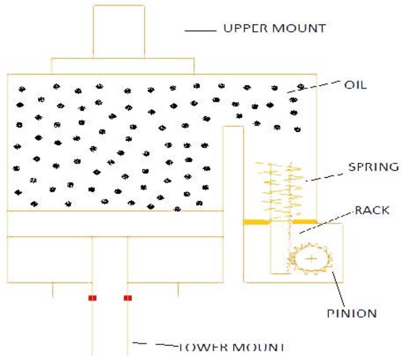


Figure 14. Regenerative Shock Absorber of Dispesh

In 2017, Mustafa [85] designed a hybrid regenerative shock absorber containing hydraulic and electromagnetic (EM) damper mechanisms to generate electricity. The connection between shock absorber, hydraulic circuit and other hydraulic components is provided by using standard self-closing couplings. The bidirectional movement on the two divisions of shock absorbers cylinder is directed into one way rotation by the four check valves of the hydraulic circuit.

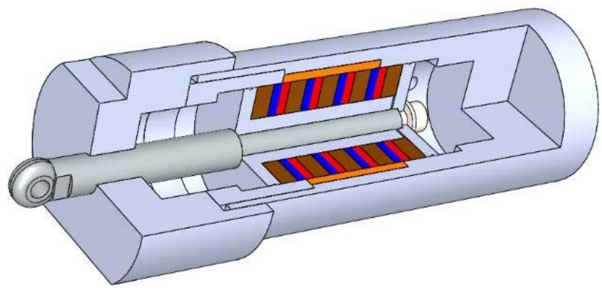


Figure 15. Half-Section View of The Hybrid Regenerative Damper

Yu et al [9-10,44-55] apply a ball screw type shock absorber. The team use a ball-screw type brushless motor suspension to conduct a more detailed design. Relevant electrical characteristics and passive dynamic responses are tested, and the feasibility of the actuator is initially verified. Subsequently, the full-vehicle bench test is used to test the energy-supply characteristics and suspension characteristics of the designed suspension system. On this basis, the influence of the motor constant on the dynamic performance and the effect of shock absorb are analysed, and the electronic control system of the motor actuator is designed. The results show that the suspension system can recover a certain amount of energy based on the driving characteristics of the vehicle under the low-frequency and large-amplitude excitation conditions. However, under the conditions of high-frequency excitation, the suspension system has poor performance.

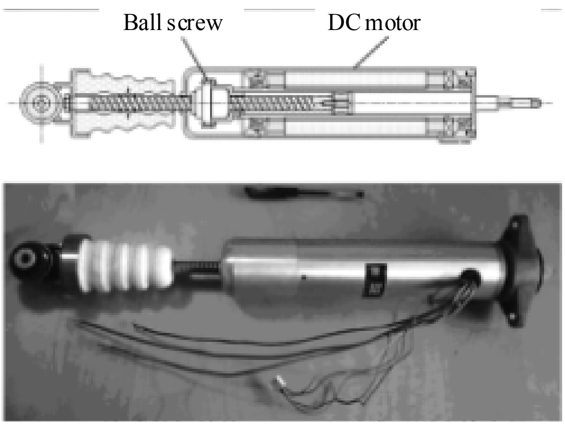


Figure 16. Ball Screw Damper of Shanghai Jiao Tong University

Wang et al [8,56-58] study the rack and pinion suspension. The mechanism converts linear vibration into motor rotation, converts the damping torque of the motor into a damping force and converts the mechanical energy into electrical energy so as to realise energy recovery. In this scheme, a clutch is installed in series between the rack pinion and the generator. After the scheme is determined, a simulation analysis is performed. It is considered that the suspension has practical application value, but the scheme is still in theoretical study and lacks practical verification.

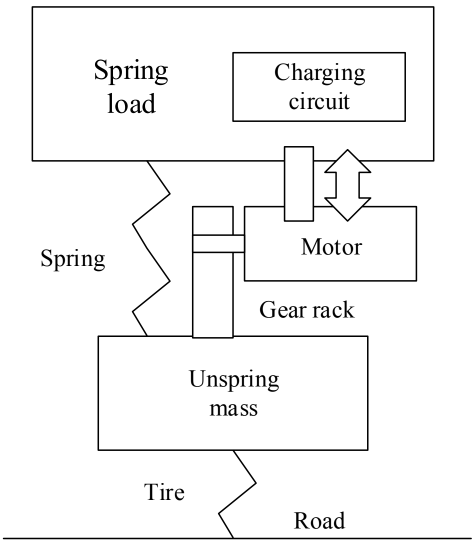


Figure 17. Rack & Pinion Suspension System of Jilin University

He and Chen [59-63] propose a hydraulic energy-regenerative suspension which converts the vibration energy between the axle and the sprung into hydraulic energy for use in automotive equipment while maintaining good and smooth vehicle running. The study shows that the mechanical properties of the energy-regenerative device are mainly reflected by the viscous damping parameters and Coulomb damping parameters. Then, the dynamic model of the suspension system is created and several numerical simulations are performed.

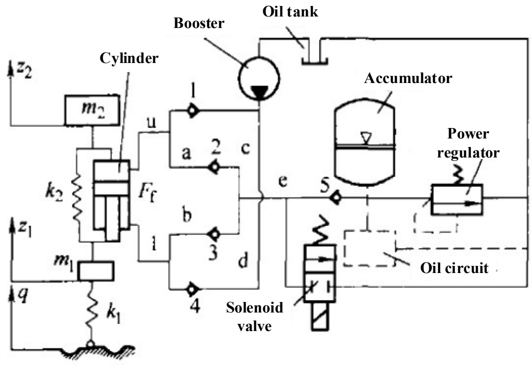
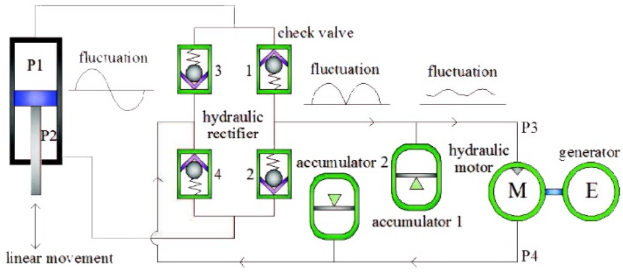
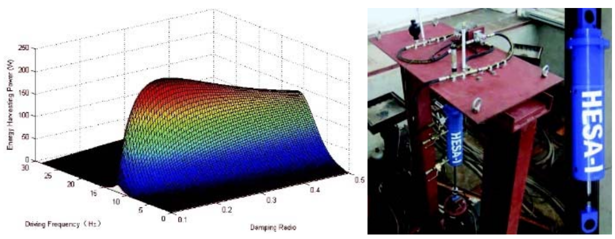


Figure 18. Energy-regenerative Suspension of Jiangsu University

Guo et al. [64-76] employ a hydraulic-electric shock absorber (HESA). The research confirms the feasibility of the energy recovery program through the simulation analysis, and introduce active control into the designed shock absorber system. The piston of the hydraulic cylinder is driven to reciprocate the cylinder under external stimulus, the hydraulic fluid flows through the hydraulic rectifier from the specified ports during the compression and extension of the piston movement, and then the fluid flows through the accumulator for stabilising the fluctuations of the fluid waves before it passes through the hydraulic motor to drive the generator for electricity. The electric energy can charge a battery or supply to the vehicle on-board equipment directly. In addition, the damping model of the hydroelectric energy-absorbing shock absorber is theoretically analysed. The PID control system is also applied to achieve the function and confirmed the damping of extension stroke is greater than that of compression.



(a) The schematic of HESA



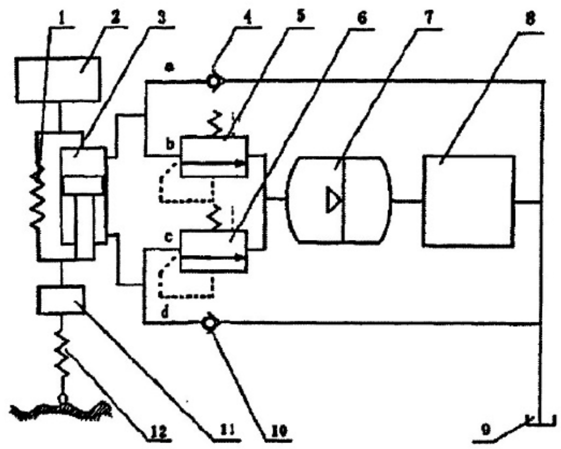
(b) Energy recovery power (c) Prototype structure and test chart

Figure19. Hydraulic-Electric Shock Absorber

To summarise the above-mentioned researches about the structure of regenerative shock absorbers. Recently, the main types of regenerative shock absorbers are the following six types:

(1) Hydrostatic energy-storage type

The configuration of the hydrostatic energy-storage energy-regenerative suspension is shown in the following Figure 20. The working principle is to convert the vibration energy consumed by the suspension system into hydraulic energy, which is stored for the use of hydraulic energy-consuming components on the suspension system.



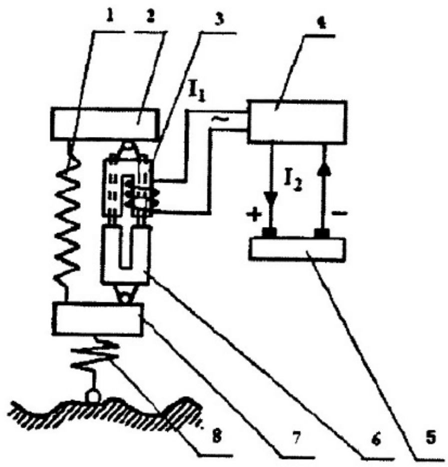
1-Suspension springs 2-Sprung masses 3-Cylinders 4, 10-Check valves 5, 6-Power regulators 7-Accumulator 8-Hydraulic Energy Dissipation Kit 9-Oil box 11-Axle Quality 12-Tire Equivalent Spring

Figure 20. Schematic of hydrostatic energy-storage suspension

The hydrostatic energy-storage type suspension is operated by a hydraulic system. The work of system is stable, but the energy recovery efficiency is low. Most of the vibration energy is still dissipated in the form of heat, and the system requires high sealing performance. In addition, the weight of system and the cost are required.

(2) Electromagnetic coil type

The electromagnetic coil suspension structure is shown in the figure below. The working principle is to replace the traditional shock absorber with an electromagnetic coil device. It can convert the vibration energy dissipated by the system into electrical energy and store it in the battery.



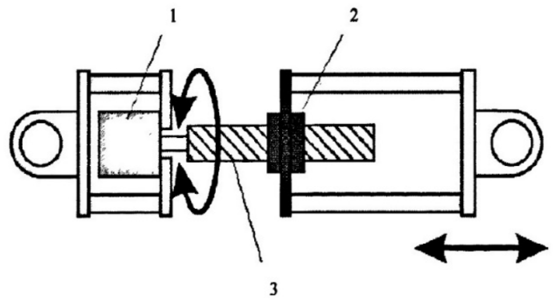
1-Spring 2-Sprung mass 3-Coil 4-Rectifier 5-Battery 6-Permanent magnet 7-Axle mass 8-Tire

Figure 21. Electromagnetic coil suspension

The electromagnetic coil type suspension has a simple structure with a low cost. According to the small magnetic pole gap, it may cause system damage. In addition, the copper loss increases and the efficiency becomes low. Therefore, the electromagnetic coil suspension structure is still in the theoretical stage at present.

(3) Ball screw type

The working principle of ball screw shock absorber is to replace the traditional shock absorber with a ball screw mechanism. When the shock absorber reciprocates with the road bump, the ball nut moves up and down, driving the screw and the electric motorin order to generate electricity for reuse.



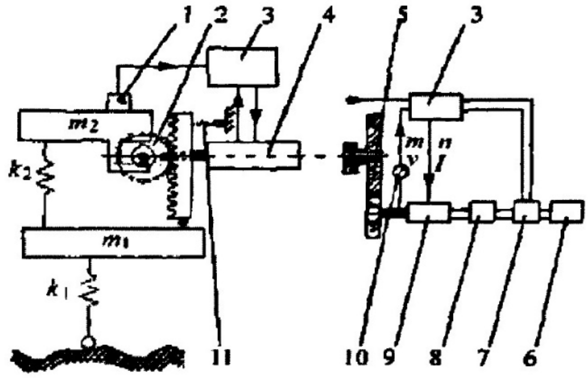
1-Motor 2-Ball nut 3-Screw

Figure22. Ball screw type shock absorber

The ball-screw type shock absorber has strong anti-interference ability, high reliability, small size, and high transmission efficiency, but the rotational friction caused by the positive and negative rotation of the motor will reduce the durability of the entire system.

(4) Rack-pinion type

The rack-pinion suspension structure is shown in Fig.23. The working principle is to replace the shock absorber with a motor and a rack-pinion mechanism. The mechanism maintains engagement under the action of spring compression and transfers vibration energy to the generator for electrical energy. The generator also provides damping force through the rack-pinion structure.



1-Acceleration Sensor 2-Rack & Pinion Mechanism 3-Control Unit4-Generator Set 5-Speed Up Gear Set 6-Electrical load 7-Battery 8-Rectifier 9-Generator 10-Speed sensor 11-Pressure spring

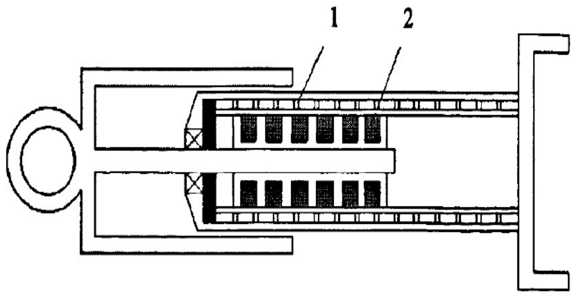
Figure23. Schematic View of Rack-pinion Suspension

The rack-pinion suspension mechanism has a good fitting relationship and high regenerative efficiency.

However, when the road surface excitation is too large, or when the usage time is too long, the rack and pinion will fail to response the excitation from road.

(5) Linear motor type

The structure of the linear motor shock absorber is shown in the Figure 24. The permanent magnet and the coil are relatively displaced when the vehicle vibrates, so that the magnetic induction wire is cut to generate electricity. The structure converts linear motion mechanical energy into electric energy directly, intermediate conversion and transmission mechanism is not required.



1-Tape 2-Coil

Figure 24. Schematic of Linear Motor Shock Absorber

The configuration of the linear motor type energy-feeding vibration absorber is relatively simple, but the generator leakage flux is the key drawback and the electrical performance is also very low, so the power generation efficiency is generally, and the vibration damper support structure is easy to fail, and the production cost is high.

(6) Hydraulic electromagnetic type

The configuration of the hydraulic electromagnetic type shock absorber is shown in the following figure. The hydraulic cylinder piston drives the oil to flow toward the accumulator under the excitation of the external, then the oil is sent to the hydraulic motor to drive motor rotates, which will drive the generator to generate electricity.

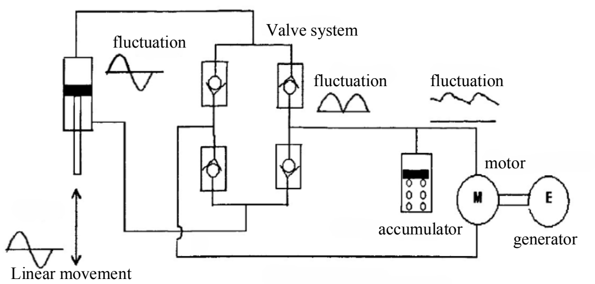


Figure25. Schematic diagram of the hydroelectric shock absorber

The specified design applies the coupling of the mechanism, liquid and electricity, which is flexible in arrangement higher recovery efficiency. The accumulator also provides a stable working state, but there are still some difficulties in the real-vehicle installation and application for there are many structural elements.

TABLE 1 PERFORMANCE COMPARISON OF SHOCK ABSORBER

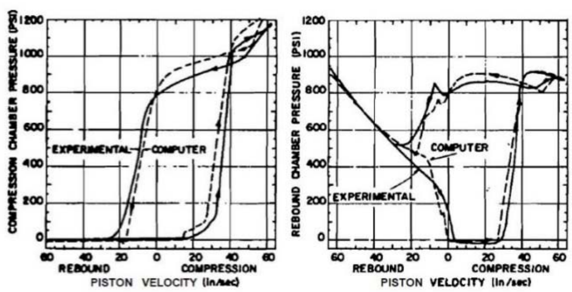
Structure Type	Efficiency	Cost	Reliability
Hydrostatic energy-storage	Low	High	High
Electromagnetic coil	Low	Middle	Low
Ball screw	High	Middle	High
Rack-pinion	Middle	Middle	Middle
Linear moto	Middle	High	Low
Hydraulic electromagnetic	High	Low	High

As shown in the above table, the main structures of the current shock absorbers are integrated. It is found that the hydrostatic energy-storage type and the electromagnetic coil type shock absorber capture a part of the energy losses by suspension, and most of the vibration energy dissipated in the form of heat, so the efficiency is low. In contrast, the electromagnetic structure has high efficiency and reliable structural design, especially the structure of the hydraulic electromagnetic structure is excellent, which has great development potential.

IV. RESEARCH ON MODELING METHOD OF REGENERATIVE SHOCK ABSORBER

The methods of numerical modelling and simulations can effectively shorten the time to complete a study. The section introduces the modelling methods of regenerative shock absorbers.

Segel and Lang [77] applied an 82-parameter model to calculate the damper characteristics. In the paper, a shock absorber is constructed by using each parameter element interconnected to simulate the performance of the shock absorber under dynamic conditions. Analysing the simulation results and the actual measurement, the relationship between the piston pressure and the piston speed of the shock absorber is obtained, including the pressure value of model and the predicted.



(a) Compression stroke (b) Stretch stroke

Figure26. Comparison between model predicted pressure and actual measured pressure

Martins [29] applied a three-degree-of-freedom quarter suspension model. The model considers the effects of vehicle mass, sprung mass, and ground excitation on suspension. The paper also carries out simulation calculations and obtains the acceleration characteristics of the shock absorbers in active and passive suspension systems.

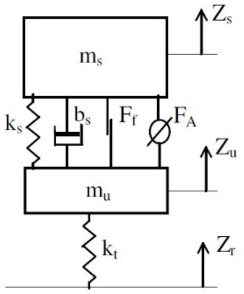
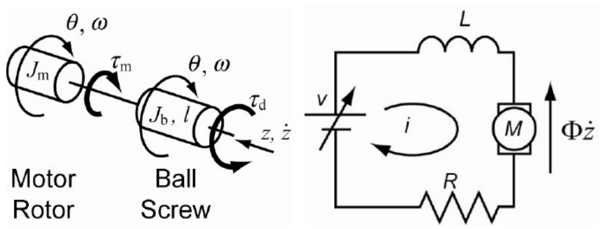


Figure27. 3DOF suspension model diagram of Martins

Suda [7] applied an electromagnetic shock absorber model based on the electromagnetic system. The model considers the quality of the line and the shock absorber, which is a four-degree-of-freedom vehicle model.



(a) Motor and Shock Absorber (b) Electromagnetic System

Figure28. Electromagnetic Shock Absorber Model of Suda

Zuo L [36] aplied a finite-element analysis method to model the magnetic field in the electromagnetic energy-regenerative shock absorber.

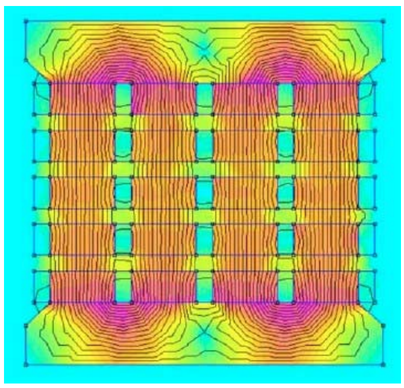


Figure 29. Finite Element Analysis of Magnetic Field

Xu et al. [78] [81] established a mathematical model of a double cylinder hydraulic shock absorber. The model considers the influences of compensation valve and the flow-through valve. Moreover, the influence of structural parameters on the damping force of the shock absorber is analysed. The AMESim software is applied to establish the model of the shock absorber, and the reliability of the AMESim model is verified by experiments. The results show that the simulation model can be used to guide the performance of the shock absorber.

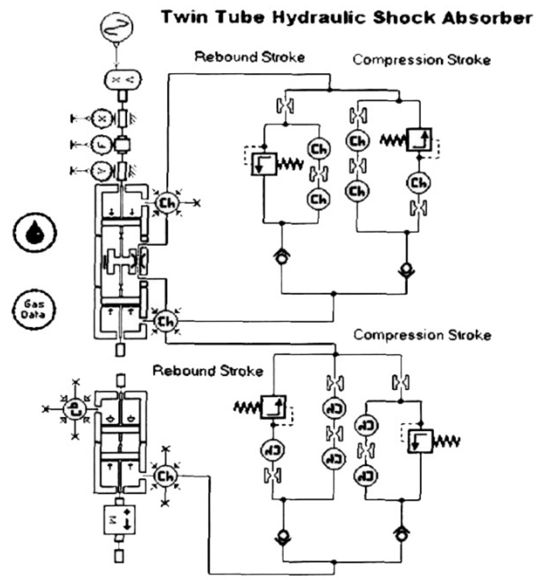


Figure30. AMESim Simulation model of Shock Absorber

Li et al. [79] conducted a modelling study on the shock absorber spring valve. The team uses the Qian's perturbation method to solve the problem, and gives the deformation perturbation solution of the damper spring valve based on the assumption of large deflection. Then the bench test of the damper speed characteristics is performed, the simulation results are also consistent with the test results.

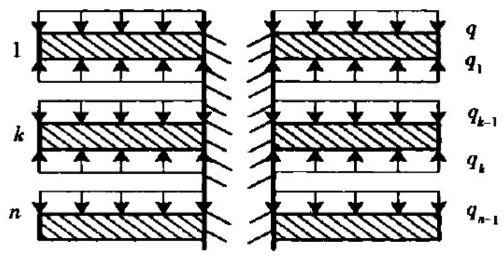


Figure 31. Fixed-Distribution Ring Plate Model

Zhang [80] established a virtual prototype model of shock absorber through the hydraulic system modelling software EASYS. The paper combined a prototype model and established a quarter vehicle model and a random road model for vibration analysis using MATLAB/Simulink software. The results show that the shock absorber model has a good performance to simulate the vibration damper operating characteristics, which can effectively attenuate vibration and improve vehicle smoothness.

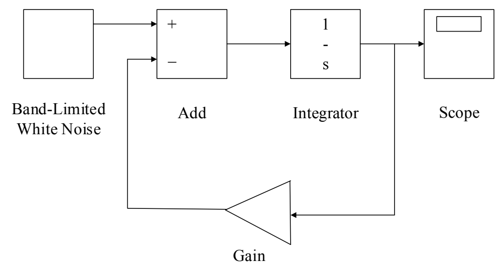


Figure 32. Surface excitation model of Class B road

Li [82] analysed the characteristics of AMESim and MATLAB/Simulink, then applied the two together to model and simulate the active suspension. The model solves the problem of co-simulation interface, which can not only bring out the outstanding fluid mechanical simulation effect of AMESim, but also take advantage of MATLAB.

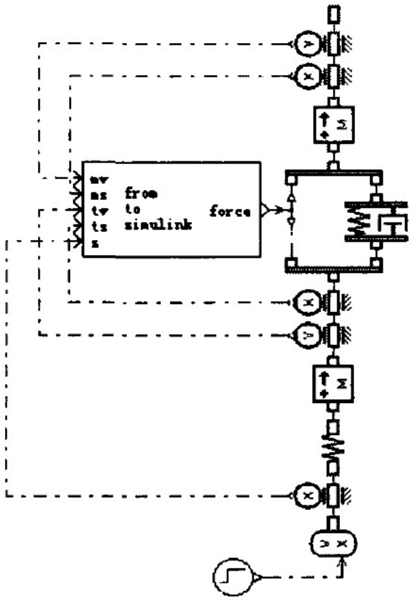


Figure33. AMESim Model of Shock Absorbers

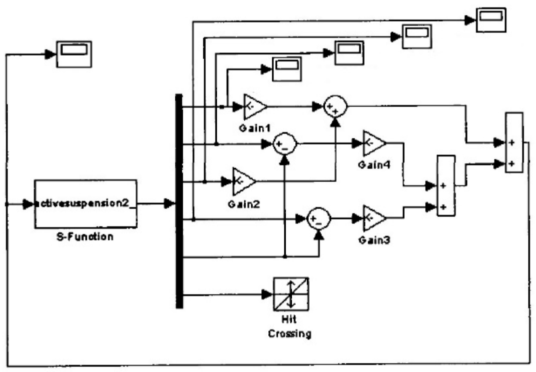


Figure34. MATLAB Simulation Model of Shock Absorbers

In above, researchers propose a series of modelling methods for the regenerative shock absorbers including the road surface excitation model, the quarter vehicle model, the four-degree-of-freedom suspension model, the finite element model of electromagnetic field, the valve mechanics model and the AMESim-MATLAB co-simulation model etc. In general, the application of computing software to establish an equivalent model not only reduces the amount of calculation, but also allows for more complex operating conditions to simulate a more realistic conditions. Combined with the practical test, the modelling method has benefits improve the performance of the shock absorbers.

V. CONCLUSION

The paper reviews the background of research on regenerative shock absorber, and studies the vibration energy recovery potential of automobile vehicles. Then, the structures of the regenerative shock absorber are summarised and classified, which states the hydraulic liquid-electric regenerative shock absorber can provide better performance and regenerated energy interms of its specific design. Finally, some other approaches of modelling and simulating are introduced for follow-up work.

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