A Comprehensive Review on Regenerative Shock-absorber Systems

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Abstract

Purpose Regenerative shock-absorber systems have become more attractive to researchers and industries in the past decade. Vibration occurs between the road surface and car body when driving on irregular road surfaces. The function of regenerative shock absorbers is to recover this vibration energy, which can be dissipated in the form of heat as waste. In this paper, the development of regenerative shock absorber is reviewed.

Methods This paper first introduces the existing research and significance of regenerative shock absorbers and reviews the potential of automotive vibration energy-recovery techniques; then, it classifies and summarises the general classifications of regenerative shock absorbers. Finally, this study analyses the modelling and simulation of shock absorbers, actuators and dampers.

Results and Conclusions Results show that the great potential of energy recovery from automobile-suspension vibration. And hydraulic and electrical regenerative structures exhibit excellent performance, with great potential for development. Regenerative shock absorbers have become a promising trend for vehicles because of increasingly prominent energy issues.

Keywords: Regenerative shock absorber, Suspension, Vibration energy, Structure, Modelling, Simulation

1 Introduction

As a convenient means of personal transportation, automobiles have spread to thousands of households with the sustained and rapid development of China's economy. By the end of 2017, the number of civil automobiles in China reached 217.43 million, an increase of 11.8% over the end of the previous year, of which 186.95 million were private automobiles (an increase of 12.9%). The number of civilian cars increased by 12.18 million, an increase of 12.0%, of which 11.416 million were private cars (an increase of 12.5%) [47]. Meanwhile, this explosion of cars has produced a series of problems, such as huge energy consumption, serious waste of resources, deepening environmental pollution, etc. Around 10% to 16% of the fuel energy that is only used to propel a car is wasted on road friction and hot exhaust resistance. The kinetic energy loss of suspension shock absorbers is one of the main energy-dissipation phenomena [61]. To cope with these increasingly tense energy and environmental problems, improving energy efficiency and green coordinated development is very important to research energy-recovery technology.

During driving, relative movement occurs between the frame and the body because of the road surface’s roughness, steering, braking, and other incentives to the wheels. This movement is not conducive to the stability of the car, reduces the comfort of the ride, and induces harmful wear and tear on the car’s components. Suspension is an appliance that accelerates the attenuation of frame and body vibration to improve ride comfort. When the frame and axle perform reciprocating relative motion, the piston in the shock absorber also performs reciprocating motion in the cylinder. The hydraulic oil in the shock-absorber shell repeatedly flows from one cavity to another through narrow pores. At this point, the friction between the hole wall and the oil and the internal friction of the liquid molecules forms a damping force on the vibration, and the vibration energy of the body and frame are converted into heat energy, which is absorbed by the oil and shock-absorber shell and then dispersed into the atmosphere [7]. Conventional automobile shock absorbers convert the mechanical energy that is generated by vibration into heat energy that is dissipated into the air, thus achieving the purpose of vibration reduction and improving the smoothness of the ride. If we assume that the dissipated vibration energy of the car is approximate to 400 W and the energy-recovery efficiency is around 60%, then the fuel efficiency can be improved up to 2.5% [37]. Therefore, this approach can reduce the energy consumption and improve the endurance of the car, thus saving energy and reducing emissions if the dissipated energy can be recovered and utilised.

In this paper, the research background of regenerative shock absorbers is introduced, and the potential of vibration-energy recovery in automobiles is studied in the second section. The structure of regenerative shock absorbers is classified and summarised in the third section. In the fourth section, the relevant modelling and simulations are introduced for follow-up work.

2 Research on the recovery potential of automobile vibration energy

Energy, which is considered crucial to global development, exists in the form of electric energy, chemical energy, thermal energy, mechanical energy and so on. For cars, most of the energy that is generated by generators is used to overcome resistance. The vibration energy of suspension systems is dissipated in the form of thermal energy. Therefore, research on the energy dissipation of recyclable suspension has become an important research direction of different countries, institutions and researchers [63]. Many researchers have conducted related research on the energy recovery of vehicle vibration over the past 30 years. This section mainly introduces the research status of the energy-recovery potential of automobile-suspension vibration.

In 1982, Segel and Lu [52] analysed the influence of road-surface elevation profiles on vehicle resistance. The results showed that the energy dissipation of suspension shock absorbers is related to the road’s roughness and speed. In addition, this paper explored the influence of road surfaces (road roughness and irregularities), tires and suspension damping on the driving resistance of vehicles. Studies showed that the energy that is dissipated by suspension shock absorbers is approximately 200 W when the vehicle travels at a speed of 48 km/h.

In 1987, Wambold et al. [60] analysed the energy dissipation problem of suspension shock absorber when the vehicle is running on the road. The results show that the energy dissipated by each suspension shock absorber is approximately 40-60 W.

In 1996, Ping [51] discussed the application of electric motors as the main actuator of active suspension systems for road vehicles. This study focused on the recovery characteristics of system power, identifying the potential recoverable power by using a quarter-suspension model with linear quadratic optimal control and based on power-spectrum density analysis and computer simulations.

In 2007, Kawamoto et al. [31] determined that each suspension shock absorber could recover 15.3 W of energy when the vehicle travelled on a C-class road at a speed of 80 km/h. The results showed that an active system in a midsize passenger car can recover around 100 W of power per wheel on a motorway, and approximately 400 W of energy can be recovered at a speed of 48 km/h.

In 2009, Yu et al. [72] applied the CARSIM simulation software to model and simulate a vehicle and completed the energy-consumption calculation of a suspension-system shock absorber when the vehicle was driving at variable speeds on different roads. The results showed that the energy dissipation of the shock absorber comprised 42.3% of the engine output power when the car was driving on the road at a speed of 10 m/s. The simulation results of a CARSIM vehicle are shown in Fig. 1.

In 2010, Yu et al. [74, 75] conducted a feasibility study of active suspension in an energy-regeneration vehicle. The simulation results showed that the energy that was dissipated by the suspension was around 651 kJ when the car travelled for 20 s on a Class-C road surface at a speed of 20 m/s.

In 2013, Han et al. [25] built a dynamic simulation model of a suspension system and tested when the vehicle's speed was 30 km/h. The recoverable energy of the shock absorber on Class-A, -B, -C, -D and -E roads was 2.08 W, 8.33 W, 33.34 W, 133.37 W and 533.21 W, respectively. The higher the grade of the road was, the more energy that could be recovered. The figure below shows the accumulation of recoverable energy over time on a Class-B road surface at a speed of 10 km/h. The analysis of recoverable energy from suspension is shown in Fig. 2.

In 2015, Khoshnoud et al. [32] estimated the energy consumption of an automobile-suspension model. This research showed that the recoverable energy was related to the bounce, pitch and roll motion of the car. In the test, the automobile was excited by four exciters and measured by linear variable differential transformers. When the excitation frequency was 20 Hz and the amplitude was 5 mm, the recoverable energy of the suspension shock absorber in the bouncing, pitching and roll modes was 970 W, 1482 W and 1572 W, respectively. The automobile suspension energy-consumption estimation devices are shown in Fig. 3.

Fundamentally, vehicles are stimulated by the road while driving, which interferes with the chassis and body of the vehicle and thus causes vibration in the suspension system. Research works and studies showed that four main factors influence the recoverable vibration energy: 1) the roughness of road surface, 2) the running speed, 3) the stiffness and damping of the suspensions/tires, and 4) the load of the vehicle. Therefore, the energy dissipation of automobile-suspension shock absorbers depends on many factors. The more uneven the road surface, the faster the driving speed and the heavier vehicle load, the greater the recovery potential of vibration energy can be reached.

3 Research on the structures of regenerative suspension/shock absorbers

Scholars began to study regenerative shock absorbers in automobiles because of the great potential of energy recovery from automobile-suspension vibration. Domestic and international research on the structures of regenerative shock absorbers in automobiles is introduced in this section.

3.1 Overview on the research of structures

In 1990, Aoyama [4] developed a hydraulic full active suspension by using the oil pump as the power source to generate pressure and balance the external force of the vehicle, so the suspension system could freely and continuously control the movement of the vehicle to improve the ride’s comfort and handling. The suspension system’s actuator consists of a hydraulic cylinder, accumulator and damping valve, connecting the hydraulic cylinder on the left side of the body with the right side to form two independent hydraulic circuits to use recovered energy to improve the ride’s comfort. This suspension system is considered a prototype of regenerative shock absorbers. Hydraulic full active suspension system from Nissan is shown in Fig. 4.

In 1991, Wendel and Stecklein [64] proposed a regenerative active suspension system that uses four separate variable displacement pumps that are connected to the same shaft to drive separate suspension units by means of exporting oil from both ends of the hydraulic cylinder to the motor, which preliminarily recovers energy from shock absorbers. This system also provides corresponding energy-saving characteristics and control strategies. Wendel’s regenerative active suspension system is shown in Fig. 5.

In 1992, Fodor and Redfield [22] designed a variable linear-transmission device. This paper introduced the concept of regenerative damping in a vibration controller and noted that the vibration energy of the suspension is usually dissipated by passive viscous-shock absorbers. Therefore, the analysis of shock absorbers in typical passenger vehicles was conducted under ideal operating conditions for the active components of the device. The results showed that regenerative vibration control was feasible and could provide almost the same damping as passive viscous-shock absorbers to store damping energy.

In 1996, Okada and Harada [48] proposed a regenerative shock absorber and suspension system for use in active shock absorbers to reduce energy dissipation without losing damping efficiency. In 2005, Okada and Ozawa [50] introduced active vibration control into regenerative shock absorbers to improve the vibration-reduction capacity through regenerative energy. This measure is applicable to dynamic load-type shock absorbers, which use PWM boost choppers to solve the dead-zone problem under the control of energy regeneration. However, energy regeneration and active control modes cannot run simultaneously. In 2008, Okada et al. [49] improved the energy-regeneration system and applied an active control algorithm to the same actuator to produce good damping performance in low-speed electric actuators. The results showed that this system had better performance than passive suspension systems and could recover vibration energy. Regenerative-suspension and shock-absorber system are shown in Fig. 6.

In 1996, Suda [54, 55] proposed a hybrid suspension system with active control and energy regeneration. In an ordinary passive suspension system, the shock absorber converts the vibration energy into heat energy to consume the vibration energy. Active suspension systems have good vibration isolation but consume extra energy. Therefore, this paper proposed a method to solve these problems in active and passive suspension systems. The vibration energy was converted into an energy-regeneration damper system that could recover energy in a passive suspension system. This hybrid power system combines this energy-regeneration system with active control to achieve good vibration reduction by consuming energy.

In 1999, Nakano et al. [42] applied the active vibration-control method of regenerative vibration energy to the self-powered active control of a heavy truck cab based on the research of Suda. In this system, the generator that was installed in the chassis suspension retrieved and stored the vibration energy in the condenser. The actuator in the cab suspension realised active vibration control by utilizing the stored energy in the condenser. In 2000, Nakano et al. [44] adopted variable resistance that was controlled by a computer to control the output force of the actuator. In practical studies, self-powered active control was realised and its isolation performance was checked to prove that the self-powered active control system had better isolation performance than semi-active or passive control systems. In 2002, Nakano et al. [46] proposed a self-powered active control system that used energy that was recovered by the energy-regeneration damper to realise active vibration control without external power supply. In this study, self-powered active control was applied to a ship’s anti-rolling system. This anti-rolling system only consisted of a motor, so the motor needed to act as an energy-regeneration damper and actuator. In 2003, Nakano et al. [45] proposed a method to calculate regenerative energy and energy consumption, which found out the trade-off between the performance and energy of the active controller by using the dynamic characteristics of the system, the feedback gain of the active controller, the specifications of the actuator and the interference of the power-spectrum density. In this system, the actuator was connected to the capacitor by relay switches that determined the current direction and variable resistors that controlled the current flow to realise self-powered active vibration control.

Between 2004 and 2007, Nakano and Suda [13, 43] improved the regenerative suspension system and proposed a new electromagnetic suspension (EMS), which could reduce the power consumption of the control system according to automatic tilting from centrifugal force. The electromagnetic dampers in automobiles were studied to improve stability and comfort. Regenerative hybrid control suspension system is shown in Fig. 7.

In 1999, Martins et al. [40] studied an electromagnetic linear actuator to replace existing active suspension. Moreover, this scheme has the advantage of recovering suspension energy. The production cost of electromagnetic actuators is costly because of material limitations, so a hybrid suspension system was proposed in this paper, combining the simplicity of passive dampers with the performance of electromagnetic active suspension. When a passive damper was used, the smaller electromagnetic actuators could maintain the performance of the active suspension. In fact, the proposed permanent-magnet linear actuator worked similarly to a permanent-magnet brushless rotating motor. The radial magnetising ring generated a magnetic field through the armature winding, the magnetising ring was installed in the magnetic-steel drive rod, and the armature winding was installed in a soft magnetic-steel cylinder to improve the closed-loop magnetic circuit. The power electronic converter switched the armature winding current according to the position of the magnetised ring. Electromagnetic linear active suspension system is shown in Fig. 8.

In 2006, Gupta et al. [24] developed a regenerative electromagnetic shock absorber, which can restore the energy that is consumed in the shock absorber. This system featured two regenerative devices: a linear device and rotary device. The linear device consisted of several very powerful permanent magnets that were mounted on the outer sleeve and moving coil assemblies that were mounted on the sliding armature. The coil moved in a magnetic field and generated electricity. The rotator consisted of a small DC motor that was connected to a lever arm by a gear system. If the lever was directly connected to the motor, the motor’s rotation could generate more output power with a given lever displacement. Regenerative electromagnetic shock absorber is shown in Fig. 9.

In 2009, a Massachusetts Institute of Technology (MIT) students [5] developed an energy regenerative shock absorber based on hydraulic transmission. This shock absorber adopted the designed hydraulic circuit to make the cylinder reciprocate to generate unidirectional fluids to drive hydraulic motors and generators to capture the energy that is generated by the relative motion of the vehicle’s suspension system. The designed regenerative shock absorber system [2, 3] attracted interest from heavy-vehicle manufacturers and the U.S. army. This test showed that each absorber could recover up to 1 kW of energy on standard roads, compared to 5 kW on rough roads. Compared to commercial vehicle alternators, this renewable energy could reduce fuel consumption of 2%-5%, and the fuel-consumption savings of military vehicles is up to 6%. Energy regenerative shock absorber based on hydraulic transmission is shown in Fig. 10.

Based on this energy regenerative shock absorber from the MIT students, LevanPower developed a regenerative hybrid shock absorber called GenShock. When the cylinder piston performs reciprocating motion, hydraulic oil flows through a check valve to the hydraulic motor, which rotates to drive the generator and generate electricity.

In 2012, GenShock Alpha and Beta prototypes [41] were installed and tested on heavy trucks that ran on freeways to compare the performance and energy regeneration. The Alpha prototype was manufactured by using commercially available components. The hydraulic motor and generator were separated from the main vibration body and driven by coaxial tube components. Although the Alpha prototype worked well with a large displacement shock absorber and was calibrated to match the impact damping curve that was provided by the truck, the energy that was recovered from the Alpha prototype was less than expected because this device could not recover energy from the small-displacement shock absorber. These Alpha systems were designed to test, model and simulate the Beta systems.

In contrast, the performance of the Beta prototype featured to improve energy regeneration, adaptive damping and active roll control in highway terrains. The optimal configuration of the hydraulic motor and generator was established through simulations and preliminary analysis, and the optimal energy-regeneration device was determined to meet the requirements of input displacement and damping performance before the Beta design. A special device called an Integrated Poston Head (IPH) was designed and manufactured to improve device integration and reduce losses: the generator and hydraulic motor were tightly coupled and mounted in the piston head of the damper. The piston-head valve integrated a hydraulic motor, generator, compression bypass valve and extension discharge valve, and its power-generation performance was greatly improved compared to the Alpha and Beta systems. When the vibration absorber’s displacement was small and the shaft speed was low, the performance of the system clearly improved. The core equipment of GenShock is ActiValve, which consists of a hydraulic pump and generator unit that is driven by an integrated electronic controller. ActiValve is used to adjust the fluid in the standard hydraulic absorber; in addition to recovering energy, this device can significantly improve ride comfort and manoeuvrability. Several Genshock hydraulic regenerative shock absorbers are shown in Fig. 11.

In 2011, Singal and Rajamani [53] studied a new type of active suspension system that combined the advantages of active and semi-active systems. This system could achieve active control to recover energy. Although the system can recover energy and achieve active control under high-frequency excitation, additional energy is required to ensure vehicle smoothness under low-frequency excitation (less than 0.8 Hz). Therefore, this system must be verified.

From 2010 to 2013, researchers [12, 35, 36, 57-59, 88, 89] studied regenerative shock-absorber systems. In 2010, Zuo et al. [88] designed and tested an electromagnetic regenerative shock-absorber system. This shock absorber was equipped with a four-phase linear engine with a rare earth permanent magnet and high-permeability magnetic ring, which had high efficiency and light weight. Around 16-64 W of energy could be recovered under the excitation conditions of 0.25-0.5 m/s in the experiment. In 2011, a new eddy-current damper has been proposed [12]. A designed damper had high efficiency and compactness and divided the magnetic field into several alternating directions to reduce the resistance of the eddy current loop and increase the damping force and damping coefficient. Electromagnetic regenerative shock absorber is shown in Fig. 12.

In 2012, a double-mass energy-recovery device was applied in terms of previous research findings [57, 59]. Vibrating energy-recovery devices usually consist of spring systems. This spring-mass system has electromagnetic or piezoelectric sensors that are connected in parallel with the spring. The two masses of the system are connected in series by an energy transducer and spring. Experiments proved that double-mass vibration energy-recovery devices could obtain more power, and the collected power of the vehicle suspension was only proportional to the tire stiffness and vertical excitation spectrum of the road. In the same year, researchers in the same group proposed and studied a new piezoelectric energy collector [35, 58, 88]. This collector had a multi-mode dynamic amplifier that could significantly increase the bandwidth and energy that was collected from environmental vibrations. This design included a multi-mode intermediate beam, or ‘dynamic magnifier’, and an ‘energy collecting beam’ with a tapered mass. The experimental results showed that the recovery capacity of the cantilever energy-recovery device was 25.5 times higher than that of traditional cantilever energy-recovery devices within the frequency range of 3-300 Hz.

In 2013, Zuo’s research group also proposed an innovative regenerative shock-absorber design [36]. This device’s advantage is that the energy-collection efficiency can be significantly improved and the impact force from vibration can be reduced. The key component is a unique motion mechanism, which we call a mechanical motion rectifier (MMR). This component can convert oscillatory vibration into unidirectional rotation in the generator. This paper introduced a prototype shock absorber with high compactness based on an MMR. A dynamic model was created to analyse the general characteristics of a moving rectifier by analogy between mechanical systems and circuits. This model could analyse electrical and mechanical components simultaneously and conduct simulations and experiments to verify the modelling and advantages. This prototype achieved over 60% efficiency under high-frequency excitation, much better than traditional regenerative shock absorbers under oscillating motion.

In the same year [90], this a comprehensive assessment of the available power for collection and the balance between energy collection, ride comfort and road traffic in a vehicle's suspension system was conducted. The results showed that the road roughness, tire stiffness and vehicle speed greatly influenced the potential harvesting power, while the suspension stiffness, shock-absorber damping, and vehicle mass were not influential. When cars were travelling at 60 mph on good roads (A/B class roads), the suspension provided an average of 100-400 W of power. Schematic diagram of mechanical motion rectifier (MMR) is shown in Fig. 13.

In 2015, Sultoni et al. [56] designed a linear electromagnetic regenerative shock absorber for passenger vehicles. This linear generator consisted of two components: a three-phase winding was placed in a primary iron-core groove, and a permanent magnet was connected to the core of the shock absorber. This design can absorb vibration energy and provide an energy source for the control system. In addition, this shock absorber uses a permanent-magnet DC motor to harvest the potential power. This electromagnetic regenerative shock absorber system is shown in Fig. 14.

In 2016, Galluzzi et al. [23] studied a type of regenerative shock absorber with hydroelectric transmission, which transfers mechanical power between linear and rotating domains. In this system, the motor is rigidly connected to a hydraulic motor with a fixed displacement, and its inlet is connected to the chamber of the linear hydraulic actuator through two pipelines. Therefore, the linear motion of the piston causes fluid flow in the hydraulic circuit, ultimately causing the motor shaft to rotate. If properly controlled, the motor can change its damping behaviour. This device also generates electricity that can then be stored in batteries. This study highlighted the use of motion rectifiers to improve energy recovery by limiting motor motion to a single rotation. This strategy can potentially reduce inertia problems that are associated with zero-speed crossover and motion reversal, thus achieving better conversion efficiency. Schematic diagram of hydraulic regenerative shock absorber and rectifier is shown in Fig. 15.

In 2017, Demetgul and Guney [14] designed a hybrid regenerative shock absorber, including hydraulic and electromagnetic (EM) shock absorbers to generate electricity. This device consists of two main components: a conductor and converter. The conductor consists of cylinders and coils, while the converter consists of piston mechanisms with permanent magnets and magnetic poles. This hybrid regenerative shock absorber is shown in Fig. 16.

Yu [6, 27-29, 70, 79-85] developed a ball screw-type regenerative shock absorber. This research investigated the energy consumption of passive suspension through damping and the energy demand of active suspension [85]. The results showed that active suspension with a vibration energy-regeneration function is very valuable. To mitigate the slow response and high energy consumption of hydraulic active suspension, the researchers designed an energy-regeneration suspension system [79]. This suspension motor actuator consists of a permanent-magnet DC motor with a ball screw and nut. The remarkable feature of suspension is that the vibration energy from road excitation can be regenerated and converted into electrical energy and maintain good suspension performance at the same time. Zheng [83, 84] modelled and simulated a suspension system and designed a prototype motor actuator. This ball-screw type energy regenerative actuator is shown in Fig. 17.

Yonghui et al. [70] designed an electronic control system for a motor actuator based on a brushless DC motor that was combined with a ball-screw structure. Cao [6] determined the structural design of the elastic components, ball screw, brushless motor and other important components, analysed the output characteristics, and preliminarily verified the feasibility and effectiveness of the motor actuator. Zhang [80-82] conducted an experimental study on regenerative electric suspension. The results showed that the electric suspension in the following state could guarantee the performance of the vehicle and return some of the electric energy at low frequency and high amplitude. Huang [27-29] established a vehicle-suspension and control-circuit model and performed a coordination analysis of the dynamic performance and effect of regenerative suspension based on the characteristics of electric regenerative suspension, which could recover vibration energy from pavement. This simplified analysis of the motor-control circuit model could elucidate the range of the control current when the electromagnetic actuator achieved reciprocating motion. The model predictive control (MPC) method was used to design the full active and semi-active main loop controllers.

The results indicated that this regenerative suspension system could recover a certain amount of energy under the conditions of low frequency and large amplitude excitation while ensuring the driving characteristics of the vehicle. Under the condition of high frequency excitation, the vibration-damping performance of the suspension system was poor and the reliability and stability of the system were insufficient. Prototype of regenerative shock absorber and test platform are shown in Fig. 18.

Wang [34, 39, 71, 73] developed a ball screw-type regenerative suspension system. Yu [71, 73] analysed the energy-saving potential of regenerative suspension and established and tested a vehicle model of semi-active regenerative suspension. This mechanism converted linear vibration into motor rotation, motor-damping torque into damping force, and mechanical energy into electrical energy to play the role of energy recovery. To reduce the layout space of ball screw-type shock absorbers, Li [34] arranged the regenerative motor at the top and added a ball-screw mechanism in the design to transform the vertical motion between sprung and un-sprung masses into the rotation of the motor rotor, adding two overrunning clutches to ensure that the motor rotor rotated in a single direction. Liu [39] further presented screw and motor serial and parallel connections of two types of structure, changing bidirectional rotation to unidirectional rotation. He designed a ball screw-type electromagnetic regenerative suspension structure to meet the installation requirements and realise active control. This regenerative damper is shown in Fig. 19.

He and Chen [8-11, 26] proposed a hydrostatic regenerative suspension system that converted vibration energy between the axle and sprung mass into hydraulic energy for automotive equipment while keeping the car running smoothly. A low-power hydraulic booster package was used to overcome the opening pressure of the check valve and improve the oil inlet efficiency of the regenerative hydraulic cylinder to eliminate the uncertain influence of the compressibility of the hydraulic oil on the regenerative damping force. This research showed that the mechanical properties of the regenerative device were mainly reflected by viscous damping parameters and Coulomb damping parameters; thus, the dynamic model of the suspension system was established.

Guo [15-21, 38, 65-69] designed and studied an electromagnetic-energy regenerative suspension system based on hydraulic transmission. Xu and Guo [67] summarised the structural characteristics and existing problems of existing energy-regeneration suspension system in details, proposed a hydraulic transmission active suspension system for electromagnetic-energy regeneration, introduced the working principle of hydraulic transmission electromagnetic-energy regeneration suspension, and established a corresponding dynamic simulation model [38]. To evaluate the performance of this suspension system, the comprehensive fuzzy evaluation method was used to establish the evaluation system [68]. However, the damping characteristic of this suspension system was inconsistent with traditional dampers, so the damping force had to be adjusted in real time [65, 69]. Based on the simulation software, a damping-force control method was proposed [66] and good regenerative performance for the suspension system was preliminarily realised.

Fang briefly analysed the energy dissipation of ordinary vehicle shock absorbers [15] and the development potential of regenerative suspension [20], developing a check valve system to control the direction of oil flow [19]. It designed and manufactured a shock-absorber prototype and integrated a rectification valve to ensure the check flow of oil in the loop. This system was verified by the test bench [16]. The results showed that the road excitation frequency, load resistance and damping ratio greatly influenced the energy recovery of the system [17]. The maximum load resistance and damping ratio were discussed to maximise the energy's recoverable power. Therefore, damping control is still the main problem to be solved [21]. A damping-control theory and method were presented, and active control was realised after the damping characteristics were studied [18].

The results showed that the system could recover some energy that was dissipated by the absorber. However, the leakage in this system was serious, which greatly affected the performance of the system. In addition, the integration degree of the system was insufficient. At present, this system cannot be installed on actual vehicles for work, and targeted development must be performed. This hydraulic regenerative electromagnetic shock absorber is shown in Fig. 20.

3.2 Summary of structural research

The above research on the structures of regenerative suspension and shock absorbers is summarised. At present, the main types of regenerative suspension or shock absorbers are as follows: hydrostatic energy storage, electromagnetic coils, ball screws, rack-and-pinion systems, linear motors and hydroelectric regenerative systems.

3.2.1 Hydrostatic energy storage

The structure of hydrostatic energy-storage regenerative suspension is shown in Fig. 21. The working principle involves converting the vibration energy that is consumed by damping in the suspension system into hydraulic energy and storing this energy in an accumulator for use in hydraulic energy-dissipating components in vehicles.

Hydrostatic energy-storage suspension depends on the hydraulic system to work; the working state is stable, but the energy-recovery efficiency is low, so most of the vibration energy is still dissipated in the form of thermal energy. This system requires high sealing with high additional quality and high cost.

3.2.2 Electromagnetic coils

The structure of electromagnetic-coil regenerative suspension is shown in Fig. 22. The working principle involves replacing traditional shock absorbers with an electromagnetic coil energy-recovery device, which can convert the dissipated vibration energy of the system into electrical energy and store the recovered energy in a battery.

The structure of electromagnetic-coil regenerative energy is relatively simple, with low cost. However, this system seems to be easily damaged from mutual collisions, small gaps between magnetic poles, and copper-loss increases, lowering the energy-feeding efficiency. Therefore, the regenerative suspension of this structure is still in the theoretical stage.

3.2.3 Ball screws

The structure of ball-screw regenerative suspension is shown in Fig. 23. The working principle involves replacing traditional shock absorbers with ball-screw mechanism. When the shock absorber moves back and forth along a bumpy road surface, the ball nut moves up and down horizontally, driving the screw and motor to rotate forward and backward and converting energy into electrical energy.

Ball-screw regenerative shock absorbers have strong anti-interference ability, high reliability, small size and high transmission efficiency. However, wear and tear from the positive and negative rotation of the motor can reduce the durability of the system.

3.2.4 Rack-and-pinion systems

The structure of rack-and-pinion regenerative suspension is shown in Fig. 24. The working principle involves replacing shock absorbers with motors and rack-and-pinion mechanisms. The mechanism keeps meshing under the action of spring compression, which transfers vibration energy to the generator and converts the kinematic energy into electrical energy. At the same time, the generator provides a damping force through the rack-and-pinion structure.

Each component of the rack-and-pinion system and suspension has a better fitting relationship and higher energy-feeding efficiency. However, the overall efficiency decreases when the road-surface excitation is too large or the use time is too long, causing gear-rack failure.

3.2.5 Linear motors

The structure of linear-motor regenerative suspension is shown Fig. 25. The working principle involves the permanent magnet producing relative displacement with the coil when the vehicle vibrates, thus cutting the magnetic induction line to generate electricity. The structure directly converts linear-motion mechanical energy into electrical energy, without any intermediate transformation or transmission mechanism.

Linear-motor regenerative suspension is relatively simple, but the generator leakage flux is large and the electrical performance is low, so the power-generation efficiency is general, the shock absorber's support structure easily fails, and the production cost is high.

3.2.6 Hydroelectric regenerative systems

The structure of hydroelectric regenerative suspension systems is shown in Fig. 26. The working principle involves the piston in the hydraulic cylinder driving oil to flow to the accumulator in one direction under external excitation. The accumulator stabilises and sends the flow to the hydraulic motor, which drives the generator to rotate and generate electricity.

Hydroelectric regenerative systems couple motor, hydraulic, and electric systems, producing a flexible layout and high recovery efficiency. The accumulator also provides a stable working state with good reliability. However, many structural components are required, impeding installation and application in real cars.

Table 1. Performance comparison of the regenerative systems of each structure

Structure type	Regenerative efficiency	Cost	Reliability
Hydrostatic energy storage	Low	High	High
Electromagnetic coils	Low	Relatively	Low
Ball screws	High	Relatively	High
Rack-and-pinion systems	Relatively low	Relatively	Relatively high
Linear motors	Common	High	Low
Hydroelectric regenerative systems	High	Low	High

The current structural types of regenerative shock absorbers are shown in the Table 1. Hydrostatic energy-storage and electromagnetic-coil regenerative shock absorbers intercept some of the energy from the original shock-absorber mechanism; most of the vibration energy is still dissipated in the form of thermal energy, so the energy-feed efficiency is low. In contrast, the electromagnetic energy-storage structure has high efficiency and a reliable structure. In particular, hydraulic and electrical regenerative structures exhibit excellent performance, with great potential for development.

4 Modelling and simulation research of regenerative shock absorbers

Modelling simulations and bench tests are usually used to study the characteristics of automotive shock absorbers. Compared to bench tests, the structural parameters are modified by engineering experience, numerical modelling simulations and software design, which can effectively shorten the research and development cycle and reduce testing losses when designing shock absorbers. This section introduces the modelling and simulation of suspension shock absorbers.

4.1 Simulation model research

As mentioned in the previous section, hydroelectric shock absorbers have attracted extensive attention from scholars because of has the characteristics of compact structure, small volume and high stability [77]. However, the modelling of shock absorbers and suspension systems is different. Scholars have also modelled hydroelectric regenerative suspension and shock absorbers to different degrees.

Fang [16, 17, 21] modelled a hydraulic electromagnetic shock absorber (HESA) system. In this model, the damping force was modelled and any pressure drops in the hydraulic rectifier and accumulator were considered. This model can accurately describe the hydraulic behaviour of the system and predict the energy-recovery ability of the system. However, this model does not consider the mechanical loss of the system. When the excitation is large, the deviation between the simulation results and test results is large. In addition, fluid loss in the cylinder should be considered in such studies. The HESA system model diagram is shown in Fig. 27.

Li et al. [33] modelled an energy regenerative shock absorber. The flow and pressure of the check valve were modelled to optimise the fluid oscillation in the hydraulic cylinder. This model can be used to analyse the regeneration performance of a generator. However, this model does not consider the effect of the battery. The regeneration efficiency of this test is only around 30%, so a more comprehensive model is required to optimise the regeneration performance. This energy regenerative shock absorber model diagram is shown in Fig. 28.

Wang et al. [62] modelled a new regenerative hydraulic shock-absorber system. This model considers the influence of hydraulic flow, rotary motion and dynamic regeneration. Research showed that the system could recover 260 W of power when the capacity of the accumulator was set to 0.32 L and the load resistance was 20 Ω. At a sine excitation of 1-Hz frequency and 25 mm, the efficiency was around 40%. This type of regenerative hydraulic shock absorber system model diagram is shown in Fig. 29.

Ahmad and Alam [1] modelled and analysed a hydraulic regenerative suspension system (HRSS). This model considers the influence of a hydraulic cylinder, hydraulic motor, generator and other applied components on the energy-feed performance of the system. The HRSS system model diagram is shown in Fig. 30.

Zhang et al. [76] modelled a semi-active suspension with a hydroelectric regenerative system. A pavement model, quarter-suspension dynamics model and semi-active suspension LQG control model are established in designed system. The model considers the hydraulic losses in the hydraulic system, such as the throttle resistance of the valve, friction resistance of the pipeline, and motor resistance, and comprehensively evaluates the regenerative capacity and damping characteristics of regenerative suspension. When the control current reaches 30 A, the HERSS energy-recovery power reaches 51.94 W, and the corresponding energy-recovery efficiency is 12.86%. The schematic diagram of semi-active suspension with hydroelectric regeneration is shown in Fig. 31.

4.2 Simulation-tool research

Models of hydroelectric regenerative suspension systems and shock absorbers mainly include the pavement, suspension, mechanical components, hydraulic components and electromagnetic components. The accuracy and effectiveness of simulation analysis are determined by the simulation method for different model objects. Scholars have also used different simulation tools to analyse regenerative models.

Chen et al. [12] used ANSYS to analyse the magnetic field of an electromagnetic shock absorber with the finite element method (FEA). ANSYS can set up the non-uniform distribution of a finite-size conductor’s edge effect and magnetic field to more accurately study the damping characteristics of eddy-current dampers. ANSYS finite element analysis of a magnetic field is shown in Fig. 32.

Zhong-Ming [86] established a mathematical model of a double-cylinder hydraulic shock absorber by using the deflection and deformation of an annular thin-plate valve plate that was subjected to a uniformly distributed load. The influence and sensitivity of the structural parameters on the damper’s damping force was analysed based on the influence of the compensation valve and flow valve on the damping force. The AMESim software was used to establish simulation models for the upper cavity, lower cavity, compensation cavity and various valve systems of the shock absorber [87] to conduct a simulation analysis of the model's damping force. The reliability of the AMESim simulation model was verified by experiments, and the simulation results can be used to guide research on absorbers' performance. The leakage simulation of a cylindrical hydraulic shock absorber is shown in Fig. 33.

Zhang [78] established a virtual prototype model of a shock absorber with EASYS, which is a modelling software program for hydraulic systems. The software of the EASY features an easy-to-use graphical modelling approach to finish the input of component model parameters and data transfer between different component models in a simple graphic interface. Users only need to use differential equations, difference equations, transfer functions, algebraic equations and other equations to establish a dynamic modelling system and connect models in the professional library to form the required system simulation model and conduct simulation analysis.

Wang et al. [62] used MATLAB to analyse hydraulic and electrical regenerative shock absorbers. MATLAB can perform simulation analyses of detailed numerical models according to the program's powerful numerical-simulation ability. In this paper, the motor, generator and other components in the hydraulic system were analysed in detail. The experimental results showed that the simulation results had good fitting degree. The verification of the damping force and feeding power of the system is shown in Fig. 34.

Jin and Deng [30] analysed the characteristics of AMESim and MATLAB/Simulink and combined these programs to simulate active suspension. The proposed method solves the interface problem of joint simulation. The approach can fully integrate the outstanding simulation effect of AMESim on fluid machinery and utilise the powerful numerical processing ability of MATLAB/Simulink to achieve excellent simulation results.

4.3 Summary of modelling and simulations

In summary, scholars have established a series of simulation models for various components of hydroelectric regenerative suspension systems and shock absorbers, including pavement-excitation models, quarter degree-of-freedom suspension models, and machine-hydraulic-electric coupling models. In particular, machine-hydraulic-electric coupling models consider the influence of steady accumulator flow, hydraulic-circuit loss, electromagnetic-field damping, motor leakage, and so on. Scholars have emphasised the establishment of simulation models for hydroelectric regenerative shock absorbers, but most of these models are not comprehensive or detailed, and some of them have not been effectively verified.

The simulation tools that have been used by scholars include ANSYS, AMESim, MATLAB, and so on. ANSYS has been used for the finite element analysis of electromagnetic models, AMESim has been used for hydraulic-system simulation, and MATLAB has been used for control-system simulation because of its powerful numerical-calculation ability. The hydroelectric regenerative shock absorbers that were studied in this paper involved pavement models, suspension dynamic models, and machine-hydraulic-electrical coupling models. A single simulation tool may not be accurate or convenient for the simulation analysis of a system. Therefore, selecting suitable software for the co-simulation provides a feasible approach and means for the research of these types of systems.

Generally, more comprehensive and detailed research is required regarding the modelling and simulation of hydroelectric regenerative shock absorbers. Using the AMEsim and MATLAB software to establish equivalent parametric models is less computationally expensive, can consider more complex working states, and can more effectively simulate the actual working state. Combined with bench tests and mutual verification, this approach can greatly reduce the workload and improve the accuracy of the dynamic performance of the designed shock absorber system.

5 Conclusions and prospects

In this paper, the recovery potential of vibration energy from automobile suspension was analysed. Converting vibration energy from suspension systems and shock absorbers into electric energy has great potential, effectively reducing the fuel consumption of vehicles. In addition, the research status of regenerative shock-absorber structures was summarised and analysed. At present, the main structural types of regenerative shock absorbers are hydrostatic energy storage, electromagnetic coils, ball screws, rack-and-pinion systems, linear motors and hydroelectric regenerative systems. This paper found that the structure of hydroelectric regenerative shock absorbers has high reliability and good regenerative performance through a comparison of shock absorbers of various structures, which has increasingly attracted the interest of researchers and engineers.

The works has been done in the past two decades mainly focused on modelling and simulations when studying hydroelectric regenerative suspension. Hydroelectric regenerative suspension models mainly include pavement-roughness models, suspension-dynamics models and machine-hydraulic-electric coupling models. Machine-hydraulic-electric coupling models consider the hydraulic-cylinder loss, accumulator action, hydraulic motor-pressure drop, power-generation loss and system-loop losses to different extents. Research findings showed the establishment of different hydroelectric suspension models, most of which have not been described in details. Therefore, the establishment of a detailed and comprehensive hydroelectric regenerative suspension model need to be the focus of future studies.

As an effective and efficient research method, simulations require appropriate simulation tools for support. This paper found that the simulation tools that have been used recently, including ANSYS, AMESim, MATLAB etc. ANSYS has been used for the finite element analysis of electromagnetic models, AMESim has been used for hydraulic-system simulations, and MATLAB has been used for control-system simulations due to its powerful numerical-calculation ability. Therefore, system models can be more effectively analysed by using multi-software co-simulations based on the complementary advantages of different software.

Generally, regenerative shock absorbers have been rapidly developed, but some deficiencies still exist:

(1) Considering only the energy-recovery performance is insufficient. More importantly, one must consider the damping performance first to ensure that the shock absorber can meet the vibration-reduction requirements of the vehicle in real applications.

(2) The problem of integrating shock absorbers with vehicles has not been fully solved. At present, most regenerative shock absorbers are still in the bench-test stage. The components of shock-absorber systems are varied, and integration problems remain to be solved.

(3) The active/semi-active shock absorbers are scarce in practical applications. Future works should be concentrate on regenerative shock absorbers that combine active/semi-active control and regenerative power level to compromise between energy-recovery and dynamic-performance requirements.

Data availability

The numerical data used to support the findings of this study are included within the article.

Compliance with ethical standards

This paper compliances with ethical standards.

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Conflict of interest

The authors declare that there are no conflicts of interest regarding the publication of this paper.

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Figure captions

Fig. 1 Simulation results of a CARSIM vehicle

Fig. 2 Analysis of recoverable energy from suspension

Fig. 3 Automobile-suspension energy-consumption estimation device

Fig. 4 Hydraulic full active suspension system from Nissan

Fig. 5 Wendel’s regenerative active suspension system

Fig. 6 Okada’s regenerative-suspension and shock-absorber system

Fig. 7 Suda‘s regenerative hybrid control suspension system

Fig. 8 Martins’ electromagnetic linear active suspension system

Fig. 9 Gupta’s regenerative electromagnetic shock absorber

Fig. 10 Energy regenerative shock absorber based on hydraulic transmission

Fig. 11 GenShock hydraulic regenerative shock absorber

Fig. 12 Zuo L’s electromagnetic regenerative shock absorber

Fig. 13 Schematic diagram of a mechanical motion rectifier (MMR)

Fig. 14 Sultoni’s electromagnetic regenerative shock-absorber system

Fig. 15 Schematic diagram of a hydraulic regenerative shock absorber and rectifier

Fig. 16 Mustafa’s hybrid regenerative shock absorber

Fig. 17 Ball screw-type energy regenerative actuator (Shanghai Jiaotong University)

Fig. 18 Prototype of a regenerative shock absorber and test platform (Shanghai Jiaotong University)

Fig. 19 Regenerative damper (Jilin University)

Fig. 20 Hydraulic regenerative electromagnetic shock absorber (Wuhan University of Technology)

Fig. 21 Schematic diagram of hydrostatic energy-storage regenerative suspension

Fig. 22 Schematic diagram of electromagnetic-coil regenerative suspension

Fig. 23 Schematic diagram of ball-screw regenerative suspension

Fig. 24 Schematic diagram of rack-and-pinion regenerative suspension

Fig. 25 Schematic diagram of linear-motor regenerative suspension

Fig. 26 Schematic diagram of a hydroelectric regenerative shock absorber

Fig. 27 HESA system model diagram

Fig. 28 Energy regenerative shock-absorber model diagram

Fig. 29 Regenerative hydraulic shock-absorber system model diagram

Fig. 30 HRSS system model diagram

Fig. 31 Schematic diagram of semi-active suspension with hydroelectric regeneration

Fig. 32 ANSYS finite element analysis of a magnetic field

Fig. 33 Leakage simulation of a cylindrical hydraulic shock absorber

Fig. 34 Verification of the damping force and feeding power of the system