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Title page

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ORIGINAL ARTICLE

Research on Multifunctional Suspension Controller Based on Bidirectional Buck-Boost Circuit

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Abstract: As is known, the active suspensions have high energy consumption problems, while energy-regenerative suspensions have limited performance in improving vibration effects. In order to make up for the contradiction between the dynamic performance of the suspension and the energy consumption, this paper uses a linear motor with a bidirectional Buck-Boost circuit to design a multifunctional controller. On this basis, Energy-Consuming Active Control (ECAC) and Regenerative Semi-Active Control (RSAC) strategies are proposed. They make full use of the motor's characteristics in different working areas and improve the scope of application of the suspension. Besides, to ensure that the motor current can accurately track the target value, the inner loop controller uses fuzzy PID to achieve it, which improves the controller's adaptability and reduces the need for the mathematical model of the control object. The simulation results show that the proposed control circuit can achieve the required control effect. Under the active control strategy, the ride comfort of the vehicle is improved by about 27%, and other performances are also controlled within an appropriate range. In the energy-regenerative mode, not only is the energy recovered, but the vehicle ride comfort is also improved by about 10%. Compared with the traditional single-performance suspension, the proposed suspension system improves the suspension's overall performance and satisfies different driving conditions and driver needs.

Keywords: Electromagnetic suspension • Bidirectional DC-DC converter • Active suspension • Energy regeneration • Hybrid model • Fuzzy PID controller

1 Introduction

The role of the suspension system is to attenuate vibrations

and impact caused by random road excitation, which determines the ride comfort and road handling of the vehicle. Among them, active suspension performance is particularly outstanding. At present, the control technology of active suspension has made significant development, such as adaptive control [1], robust control [2-3], and intelligent control [4], which can solve different control goals. Although the active suspension system is currently ideal, the problem of high energy consumption restricts its application [5]. According to the literature [6-9], the traditional vehicle suspension system has a well recovery potential. If the energy is harvested and reused, the vehicle's fuel consumption and exhaust emissions will be further reduced. Therefore, when designing a suspension controller, it is necessary to consider the damping performance and energy consumption.

Researchers have conducted much research on the recovery technology of suspension vibration energy, and different energy recovery suspension systems have their advantages and disadvantages [10]. Electromagnetic energy-harvesting shock absorbers are popular in various vibration energy recovery structures. Because they have high energy conversion efficiency, fast response speed, strong controllability, and superior energy recovery capabilities. The generator type is mainly divided into linear motor [11-14] and rotary motor [15-17]. The rotating electric machine has been developed rapidly because of its higher recovery efficiency and average power characteristics. But it is necessary to design an additional mechanical conversion structure to convert the reciprocating motion into a rotary motion. Li, Zhang and

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Guo et al. [18-20] established an energy-harvesting shock absorber that combines a rotating electric machine and a rack and pinion mechanism. Simultaneously, a motion rectifier (MMR) is used to complete the direction conversion, which improves recovery efficiency. Then the shock absorber realizes adjustable damping by controlling the size of the electric load. Another structure is to use a ball screw and a rotating motor to form an energy-regenerative damping mechanism. Chen et al. [21] proposed adjusting the electromagnetic force to fit the ideal control force by changing the number of rechargeable batteries. The semi-active suspension's recovery efficiency is as high as 77.72%, guaranteeing the damping effect. Besides, Xie et al. [22] designed an energy regenerative shock absorber composed of multiple controlled generators, where each power generation mechanism consists of two rotating electric machines and a ball screw mechanism. The damping coefficient is changing by controlling the number of generators used and adjusting the external adjustable resistance. Also, linear motors have been widely used because of their simple structure and fast response speed, and no mechanical transmission loss. Shi et al. [23] combined a DC linear motor and a three-stage adjustable shock absorber in parallel and discussed the influence of adjustable damping value on recovered power. At the same time, Shi et al. [24] also used a one-way Buck-Boost circuit to design as an energy-regenerative controller. By outputting a set of PWM signals to control the circuit is on and off, the motor current was controlled to increase the control bandwidth of semi-active control.

However, the above energy-regenerative suspension also has shortcomings. First of all, the active electromagnetic suspension that combines a ball screw/rack or rack/pinion mechanism with a rotating motor has the following drawbacks: □ Due to the addition of a mechanical conversion mechanism, the complexity of the system is increased; □ The service life of the ball screw or rack/pinion mechanism is short and requires regular maintenance; □ There are gaps and inertial mass, the system responds slowly; then, there are deficiencies in the structural design, and the control methods generally belong to the semi-active energy-regenerative control strategy. Compared with the energy-consuming active control, vehicle performance cannot be further improved. Simultaneously, the operating mode is single, which cannot meet the

complex working conditions and different driving requirements.

In response to these problems, this paper designs a bidirectional Buck-Boost transformer circuit controller, which uses the same electromechanical infrastructure to achieve energy consumption control and energy recovery. By changing the controller's power switch, suspension control and mode switching can be realized. Different control strategies are designed on this basis, and the performance and recovery efficiency of the shock absorber under different driving conditions are analyzed. The designed controller combines the advantages of energy regeneration and active control to meet different driving conditions and performance requirements. If appropriate switching conditions are selected, the suspension can realize energy self-supply.

2 System scheme design

2.1 Working principle of suspension system

In order to realize the energy recovery control and energy consumption control, the actuator adopts a linear motor structure, and the overall structure of the shock absorber is shown in Figure 1. Regardless of the mode, the control force is determined by the motor current's size which is adjusted by the duty cycle. The value of the control force is calculated by the control strategy and the sensor input signal, and then the duty cycle value is output by the current controller. To reduce the error between the actual and ideal current, the current controller composed of a fuzzy PID control algorithm is selected, which has higher accuracy and rapidity. Then, the PWM generator outputs the PWM wave to control the Buck-Boost Circuit. In the energy regenerative mode, the linear motor converts the vertical vibration's kinetic energy caused by the uneven road into electrical energy. It then inputs the electrical energy into the energy storage element through a full-bridge rectifier and a DC transformer. In the energy consumption control mode, the electric energy in the energy storage element is used to obtain the required control voltage value through the Buck-Boost Circuit, and the rectifier controls the direction of the voltage. The linear motor uses the input voltage to generate the corresponding control force to reduce the road's vibration.

Figure 1 Topology of the multifunctional suspension system

2.2 Controller circuit design

The topological structure of the controller circuit is shown in Figure 2. The linear motor can be regarded as an adjustable voltage source E plus a resistor R_m and an inductance L_m . The motor generates an induced electromotive force E under the relative motion, which is expressed as follows.

$$E = K_v \cdot v \quad (1)$$

Where v represents the relative speed between the body and the tire, and K_v represents the induced back electromotive force coefficient. However, current i_l determines the electromagnetic force f_e generated by the motor, and its magnitude is:

$$f_e = K_i \cdot i_l \quad (2)$$

Then, the switches of $S_1 \sim S_4$ form a full-wave rectifier, which converts voltages in different directions into unidirectional voltages for voltage conversion. Capacitors C_1 and C_2 are filter capacitors (filtering, energy storage, and voltage stabilization) at the input and output, respectively, which reduce the voltage fluctuations and avoid the spike voltage from damaging the circuit components. S_5 and S_6 are a pair of complementary switches that receive PWM control signals, and their on-off controls the current and voltage of the circuit and controls the switching of the input and output directions. The inductance L is the most critical part of the entire circuit and is the input and output energy carrier. It cooperates with the switches S_5 and S_6 to realize the bidirectional Buck-Boost conversion. The switch S_7 avoids the power supply energy flowing into the circuit to consume energy during the energy regenerative control. And the energy storage system can be regarded as a model of a fixed voltage source and a resistor in series.

Figure 2 Controller circuit model

3 Modelling and analysis

3.1 Suspension Model

Since the simplified 1/4 vehicle model can fully reflect the vertical vibration caused by external disturbances and can obtain the corresponding parameter response in time, the research object selects a suspension model with two degrees of freedom, as shown in Figure 3. Moreover, the road input uses filtered white noise [25].

Figure 3 Quarter vehicle model

According to the model, the dynamic equation can be expressed as:

$$\begin{aligned} m_s \ddot{x}_s &= -k_s (x_s - x_u) + f_e \\ m_u \ddot{x}_u &= k_s (x_s - x_u) - f_e - k_t (x_u - x_r) \end{aligned} \quad (3)$$

Where m_s and m_u represent the sprung mass and unsprung mass respectively; k_s and k_t are the suspension stiffness and tire stiffness respectively; the vertical displacements of the sprung mass and unsprung mass are defined as x_s and x_u ; f_e is the force generated by the linear motor, including damping force (energy regeneration mode) and control force (active control mode); x_r is the displacement of the road disturbance, and it is expressed as follows:

$$\ddot{x}_r = -2\pi f_0 x_r + 2\pi n_0 \sqrt{G_q(n_0)} v \cdot w \quad (4)$$

Where n_0 is the reference spatial frequency; f_0 is the lower cut-off frequency; v is the vehicle speed; w is the White Gaussian Noise with an average value of zero; $G_q(n_0)$ is the road irregularity coefficient.

3.2 Circuit state analysis

Since the control circuit will work in different operating states, so it is necessary to study the energy flow of the control circuit carefully to grasp its control performance. It is worth noting that the switching period T is usually tiny, and the back electromotive force E is viewed as unchanged. The suspension working mode is switched by the full-bridge rectifier and switches S_5 and S_6 .

3.2.1 Energy recovery mode

When the shock absorber is in the energy recovery state, the equivalent damping size of the shock absorber is determined by the duty cycle of S_5 and S_6 . According to this feature, different duty ratios are designed to adjust the linear motor's damping force. Nevertheless, because the circuit inevitably has resistance, there is a specific range of equivalent damping, and the control performance is limited. In this mode, the switching signal of switch S_6 is complementary to S_5 .

Figure 4 Conduction state of the control circuit in energy regenerative mode

During the time $0 < t < DT$, the circuit operation is shown in Figure 4. According to Kirchhoff's theorem, the voltage and current equation of the circuit are obtained:

$$\begin{cases} E = L_m \frac{di_1}{dt} + V_1 + R_m i_1 \\ V_1 = L \frac{di_L}{dt} \\ i_1 = C_1 \frac{dV_1}{dt} + i_L \end{cases} \quad (5)$$

At the output end, if the voltage value V_o of C_2 is greater than the recovery voltage E_c , the switch S_7 is opened; otherwise, no current flows through the battery pack. The current expression is as follows.

$$C_2 \frac{dV_2}{dt} = \frac{V_2 - E_c}{R} \quad (6)$$

According to the above formula, the state equation during the conduction period can be obtained.

$$\dot{x} = \begin{bmatrix} -\frac{R_m}{L_m} & 0 & -\frac{1}{L_m} & 0 \\ 0 & 0 & \frac{1}{L} & 0 \\ \frac{1}{C_1} & -\frac{1}{C_1} & 0 & 0 \\ 0 & 0 & 0 & \frac{1}{RC_2} \end{bmatrix} x + \begin{bmatrix} \frac{1}{L_m} & 0 \\ 0 & 0 \\ 0 & 0 \\ 0 & -\frac{1}{RC_2} \end{bmatrix} u \quad (7)$$

Where $x = [i_1, i_L, V_1, V_2]^T$ and $u = [E, E_c]^T$. When the initial state value is x_{10} , Equation 7 can be solved to obtain

$$x_1(t) = e^{A_1(t-t_0)} x_{10} + \int_{t_0}^t e^{A_1(t-\tau)} B_1 u d\tau \quad (8)$$

Figure 5 Disconnected state of the control circuit in energy regenerative mode

When $DT < t < T$, it can be seen from Figure 5 that because the inductor current cannot change abruptly at the output, it continues to maintain the initial value to charge the capacitor C_2 and the recovery battery circuit. The voltage and current equation is:

$$\begin{cases} L \frac{di_L}{dt} = -V_2 \\ i_L = C_2 \frac{dV_2}{dt} + \frac{V_2 - E_c}{R} \end{cases} \quad (9)$$

At the input end, since the induced electromotive force E plus the inductor voltage is greater than V_1 , so continue to charge the capacitor C_1

$$\begin{cases} E + L_m \frac{di_1}{dt} = V_1 + R_m i_1 \\ i_1 = C_1 \frac{dV_1}{dt} \end{cases} \quad (10)$$

The state equation during turn-off is obtained by Formulas 9 and 10 as

$$\dot{x} = \begin{bmatrix} \frac{R_m}{L_m} & 0 & \frac{1}{L_m} & 0 \\ 0 & 0 & 0 & \frac{1}{L} \\ \frac{1}{C_1} & 0 & 0 & 0 \\ 0 & \frac{1}{C_2} & 0 & -\frac{1}{RC_2} \end{bmatrix} x + \begin{bmatrix} \frac{1}{L_m} & 0 \\ 0 & 0 \\ 0 & 0 \\ 0 & \frac{1}{RC_2} \end{bmatrix} u \quad (11)$$

The state of the system is solved as

$$x_2(t) = e^{A_2(t-t_0)} x_{20} + \int_{t_0}^t e^{A_2(t-\tau)} B_2 u d\tau \quad (12)$$

Assuming the system is in a stable state, the value at the end of turn-on is equal to the initial value at the moment of a turn-off, that is

$$\begin{cases} x_{20} = x_1(DT) \\ x_{10} = x_2(T) \end{cases} \quad (13)$$

3.2.2 Energy consumption mode

In this mode, the car's electric energy is consumed to output the active control force, which greatly improves the ride comfort. The circuit's operating state is similar to that the energy-recovery mode, except that the parameters and input and output have changed.

Figure 6 Conduction state of the control circuit in energy regenerative mode

When $0 < t < DT$, the circuit is shown in Figure 6, S_6 is on, and S_5 is off. If the voltage of the capacitor C_2 is set equal to the power supply voltage E_c , no current will flow to it.

According to Kirchhoff's theorem, the following equation is obtained.

$$\begin{cases} E_c = L \frac{di_L}{dt} + R i_L \\ V_1 = L_m \frac{di_1}{dt} + R_m i_1 + E \\ i_1 = C_1 \frac{dV_1}{dt} \end{cases} \quad (14)$$

Figure 7 Conduction state of the control circuit in energy regenerative mode

When $DT < t < T$, S_5 turns on. On the output side, the inductor current flows to the capacitor C_1 and the motor while maintaining the value at the previous time.

$$\begin{cases} V_1 = L \frac{di_L}{dt} \\ V_1 = L_m \frac{di_m}{dt} + E + R_m i_1 \\ i_L = C_1 \frac{dV_1}{dt} + i_1 \end{cases} \quad (15)$$

It can be analyzed from the circuits in the above two modes that the selection of the inductor L is based on the rated current. In order to withstand a larger current, a smaller inductor value is selected, but need a higher switching frequency. The value of the capacitor has a noticeable influence on the current ripple. If C_1 is selected a larger value, the motor current can be stabilized, but a too-large value will cause a hysteresis deviation at the current zero-crossing or sudden change. Besides, C_2 has little effect on the motor current. At the same time, both capacitors will withstand the pulse voltage of the inductor L , so choose a capacitor with a higher high-frequency withstand voltage.

4 Current controller

4.1 Fuzzy PID controller

Because the Buck-Boost converter has non-linear characteristics, the mathematical model's application range derived by hypothesis or the estimated model obtained by identification is limited, and the ideal output current cannot be output accurately, quickly, and accurately. If the

traditional PID controller is selected as the current controller, there will be a contradiction between zero overshoot and rapidity. Simultaneously, the input induced electromotive force and output control current of the controller are both time-varying. They are failing to meet higher control performance requirements. Therefore, the fuzzy control algorithm is introduced into PID control to realize the adaptive adjustment of control parameters and improve its control performance [26]. The principle of the current controller is shown in Figure 8.

Figure 8 Fuzzy PID controller structure

The adaptive fuzzy PID controller takes the error e and the error differential de as input to adjust the PID control parameters for different situations. The output results of fuzzy inference are K_p , K_i , K_d , and then the duty cycle D is calculated by the PID controller.

4.2 Fuzzy membership function and control rules

The core of adaptive fuzzy PID control lies in the design of fuzzy membership functions and control rules. The fuzzy set of input variables and output variables in this paper is seven fuzzy subsets: [(PB), (PM), (PS), (ZE), (NS), (NM), (NB)], membership functions are all represented by triangles.

The database stores the membership functions of all variables' fuzzy subsets and provides data to the inference engine in the inference of fuzzy relation equations. For nonlinear, time-varying, and challenging to describe with proper transfer functions, various tuning experiences and knowledge of PID parameters can be summarized. When the deviation is large, it mainly eliminates the deviation as soon as possible; when the deviation is small, it prevents overshoot and improves system stability. According to control experience and many experiments, fuzzy rules are formulated, as shown in the Table 1.

Table 1 Fuzzy rule table

e	de						
	NB	NM	NS	ZO	PS	PM	PB
NB	NB/PB/NB	NB/PB/NB	NB/PB/NB	NB/ZO/NB	PS/NB/PS	PM/NB/PM	PB/NB/PB
NM	NM/PB/NM	NM/PM/NM	NB/PS/NB	NM/ZO/NB	ZO/NB/ZO	PS/NM/PS	PB/NB/PB
NS	NS/PS/NS	NM/PS/NM	NB/NS/NB	NS/ZO/NB	NS/NS/NS	ZO/NS/ZO	PM/NM/PM
ZO	ZO/ZO/ZO	NS/ZO/NS	NM/NM/NM	ZO/ZO/ZO	NM/ZO/NM	NS/ZO/NS	PS/ZO/PS
PS	PS/NM/PS	ZO/NS/ZO	NS/NM/NS	NS/ZONS	NB/PS/NB	NM/PS/NM	ZO/PS/ZO
PM	PM/NB/PM	PS/NM/PS	PS/NB/PS	NM/ZO/NM	NB/PB/NB	NB/PM/NB	NS/PM/NS
PB	PB/NB/PB	PM/NB/PM	PB/NB/PB	NB/ZO/NB	NB/PB/NB	NB/PB/NB	NM/PM/NM

5 Design of Suspension Control Strategy

According to the analysis of the energy flow state of the motor, Figure 9 shows that the motor can run in three intervals. Among them, in zone I and II, the motor consumes battery energy to suppress vibration. And in zone III, the motor acts as a generator to recover the vibration energy and store it in the battery. According to the characteristics of the controller, two operating strategies are designed. When the road is rough, or the battery pack is low, the energy-recovery semi-active control is used to recover energy. In this mode, only the passive damping force can be generated to offset the road vibration. Under the energy consumption control, the motor will obtain the control force from the energy

consumption of the battery. This control strategy significantly increases the range of the control current and improves the vibration reduction effect.

Figure 9 The operating zones of the motor

5.1 Energy Regenerative Control Strategy

In this mode, the linear motor is always in the generator state, and the damping can be adjusted by changing the duty cycle. So, if the equivalent damping is the value where the recovered power is the largest, the most recovered energy is obtained, but other performances have also deteriorated. To avoid the existence of the above contradictions, a skyhook control [27] with on-off characteristics is adopted.

$$c_s = \begin{cases} c_{max}, & \dot{x}_s(\dot{x}_s - \dot{x}_r) > 0 \\ c_{min}, & \text{else} \end{cases} \quad (16)$$

In the formula: c_{max} shall not exceed the maximum equivalent damping of the linear motor, and c_{min} selects the equivalent damping coefficient near the maximum recovered power.

5.2 Active Control Strategy

Under this strategy, vehicle body acceleration is the primary optimization index. Furthermore, the influence of suspension stroke, tire deflection and handling force also need to be considered. Therefore, this paper adopts the *LQG* optimal control strategy [28] to ensure the dynamic performance of the suspension. The performance index function of the output regulator can be written as follows:

$$J = \lim_{T \rightarrow \infty} \frac{1}{T} \int_0^T \left[q_1 \ddot{x}_s^2 + q_2 (x_s - x_u)^2 + q_3 (x_u - x_r)^2 + r F^2 \right] dt \quad (17)$$

Where: T is the vehicle travel time, q_1 , q_2 , q_3 and r are the weighting factors of body vertical acceleration, suspension dynamic disturbance, suspension dynamic disturbance and active output force. The weight factor selection is closely related to the researcher's choice of the focus of improving the performance of the suspension.

6 Numerical simulation and results discussion

6.1 Controller Performance

For the controller system designed in this paper, the control variable is the size of the input duty cycle, which not only controls the force of the actuator but also affects the recovery power of the battery. In order to better analyze the performance of the actuator, this paper discusses the changes in equivalent damping, recovered power and recovery efficiency by changing the relative speed and duty cycle of the suspension in the energy regenerative mode. The results of each state are obtained under stable operation. Finally, the impact of the recovery voltage on the shock absorber is discussed. The parameters of the control circuit are shown in Table 2.

Table 2 Control circuit simulation parameters

Symbol	Value	Symbol	Value
K_i	115N/A	L_m	3.3mH
K_v	76.6V/(m/s)	L	33uH
R_m	5.1	C_l	6.8uF
R	0.1	C_2	460uF

Figure 10 Equivalent damping under 12V(a) and 24V(b) recovery voltage

It can be seen from Figure 10 that the recovery voltage will not affect the value range of the equivalent damping. So the performance of the energy harvesting controller is relatively stable. As the duty cycle changes, the equivalent damping can be adjusted from 0 to 1716N/m, and the relative speed affects the rate of change of the damping.

As shown in Figure 11, the input voltage has an undeniable influence on the recovered power. So the recovery capacity on a smooth road is relatively weak. The high recovery power area is affected by the recovery voltage. Combined with the previous equivalent damping diagram, the equivalent damping of the highest power of different recovery voltages is very close, varying around 800, which provides a basis for the design of the energy regenerative controller.

Figure 11 Recovery power under 12V(a) and 24V(b) recovery voltage

Figure 12 Recovery efficiency under 12V(a) and 24V(b) recovery voltage

The changing trend of recovery efficiency is similar to the equivalent damping, as shown in Figure 12. The higher recovery efficiency point is closer to the '0' duty cycle. The reason is that when the duty ratio is low, the recovery current will be cut off, and the resistance consumption is relatively small. With the increase of the duty cycle, the charging voltage and circuit resistance consumption also gradually increases, which leads to a decrease in recovery efficiency.

6.2 Suspension Performance Analysis

In order to verify the effectiveness of the designed controller, simulations under various road conditions were performed in MATLAB® / SIMULINK® software. The simulation results of two different control modes were compared with those of traditional passive suspension systems at a speed of 15m/s on a Class D road, and the results of the other three different roads A, B, and C, are compared in Table 4 with the root mean square value. Table 3 shows the parameters used in the simulation.

Table 3 Suspension and control circuit parameters

Symbol	Value	Symbol	Value
m_s	343kg	c_{max}	1600 N/m ²
m_u	40kg	c_{min}	750 N/m ²
k_s	14500N/m	n_0	0.1
k_t	190000N/m	f_0	0.011
c_s	1385.4N/m ²		

The circuit's switching frequency is 2×10^4 Hz, and the range of errors e and de of fuzzy control are both set to $[-0.1, 0.1]$ and $[-10^{11}, 10^{11}]$, but the range of PID parameters is different for the two control strategies. The range of K_p , K_i , and K_d under active control are $[0, 2 \times 10^{-3}]$, $[100, 300]$, and $[0, 1 \times 10^{-3}]$, and the range of the three parameters under energy regenerative control is $[0, 2]$, $[2000, 3000]$, and $[0, 1]$.

According to the controller's characteristics, the recovery voltage is selected to be 24v, and the voltage for energy consumption control is set to 90V to avoid insufficient output voltage range. From Figure 13, the control force in the two modes is in good agreement with the ideal value, and the ripple of the control force is smaller because the motor inductance is much larger than the power inductor.

Furthermore, active control's tracking effect is better than energy recovery control because the former provides greater input current, which improves the response speed. The regenerative energy control has overshoot when the control force changes suddenly, but it also can meet the control requirements.

Figure 13 Comparison of ideal and actual control force in active mode(a) and energy-regenerative mode(b)

Figure 14 Comparison of dynamic performance: Body acceleration (a) time domain response and (d) frequency domain response; suspension relative displacement in (b) time domain response and (e) frequency domain; Response of dynamic tire deflection in (c) time domain and (f) frequency domain

The vehicle body acceleration (BA) response results in Figure 14(a) and Table 3 show that both active control and energy recovery control strategies can improve ride comfort, and the improvement effects are increased by 26% and 10%, respectively. At the same time, control effect does not change with driving conditions. Besides, it can be seen from Figure 14(d) that the two control methods effectively suppress the vibration near 1 Hz, but the improvement effect of the RSAC is not as good as the ECAC in other frequency because active control has a more extensive control current range.

It can be seen from the Figure14 and Table3, The

suspension relative displacement (SRD) of the RSAC and ECAC modes is reduced by about 10% in the time domain, while the frequency domain is better than the passive suspension. They are both ensures the suspension's regular operation and does not interfere with the body. The dynamic tire deflection (DTD) under the two control methods has deteriorated, especially in the high-frequency part, where the active control is much larger than the passive suspension, resulting in reduced road handing. Nevertheless, as long as the tire's relative displacement is less than 0.013m, the tire has good contact with the ground. At the same time, it can be seen from the table that the two control effects remain stable under different road conditions.

Table 3. RMS of performance indicators under different road conditions

	Road A			Road B		
	ECAC	RSAC	passive	ECAC	RSAC	passive
BA(m/s ²)	0.1822	0.2198	0.2464	0.3643	0.4396	0.4927
SRD(mm)	2.147	2.158	2.409	4.294	4.315	4.818
DTD(mm)	1.049	0.9135	0.8501	2.098	1.827	1.7
	Road C			Road D		
	ECAC	RSAC	passive	ECAC	RSAC	passive
BA(m/s ²)	0.7286	0.8793	0.9855	1.457	1.759	1.971
SRD(mm)	8.589	8.631	9.636	17.18	17.26	19.27
DTD(mm)	4.196	3.654	3.4	8.392	7.308	6.801

Figure 15 (a) Instantaneous recovery power in RSAC; (b) instantaneous power consumption in ECAC

Table 4 Controller performance on different road conditions

	Road A	Road B	Road C	Road D
Average recovery power (W)	0.56	2.43	9.96	39.50
Maximum average recovery power (W)	1.39	5.64	22.49	87.77
Average power consumption (W)	4.21	16.75	67.06	270.2
Recovery efficiency	19.92%	21.57%	22.16%	21.94%

The instantaneous power consumption and regeneration of the electromagnetic shock absorber are shown in Figure 15, respectively. Due to the recovery circuit have small resistance, the charging current drops quickly, resulting in high-frequency fluctuations in the recovery power. However, on a D-class road with a driving speed of 15m/s, the controller's average recovered power can reach 39.5W, while the average power consumption of active control under the same conditions is 270.2 W. Although the energy recovered is less than the consumption, only a reasonable switch between the two working modes can achieve energy balance. Then, from the data in the Table4, the road level has a significant influence on the control, and the recovered power in the low-level road RSAC mode is feeble, the power consumption of active control is reduced accordingly. In RSAC mode, part of the energy regeneration capability is sacrificed to improve ride comfort, while in ECAC mode, other performance will not be reduced under the premise of ensuring good ride comfort.

6 Conclusions

According to the working characteristics of linear motors, this paper introduces the design and simulation of a new type of multifunctional shock absorber based on the two-way buck-boost circuit. Two different control modes (energy-consuming active control and Regenerative semi-active

control) are proposed. By changing the circuit switch, the control force and working mode can be adjusted, which provides a physical structure basis for different suspension control strategies. In order to accurately output the ideal control force, a fuzzy PID current controller that does not require a control object model is selected, and it also solves the nonlinear problem of the Buck-Boost circuit. Besides, by analyzing the influence of the circuit parameters on the performance of the controller, the appropriate electrical components are selected. The simulation results show that the proposed controller can achieve the required control function, and the control effect under different driving conditions does not change much. In terms of ride comfort optimization, energy-consuming active control has the best effect, but cost more energy. In the RSAC mode, it not only ensures good damping performance but also recovers a certain amount of energy. If the two control modes can be switched reasonably, the proposed controller can meet different riding requirements and make up for the shortcomings of traditional strategies which use single performance optimization.

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7 Declaration

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Authors' contributions

XC was in charge of the whole trial; SH wrote the manuscript; TH and DP assisted with structure and language of the manuscript. All authors read and approved the final manuscript.

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The authors declare no competing financial interests.

Consent for publication

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Figures

Figure 1

Topology of the multifunctional suspension system

Figure 2

Controller circuit model

Figure 3

Quarter vehicle model

Figure 4

Conduction state of the control circuit in energy regenerative mode

Figure 5

Disconnected state of the control circuit in energy regenerative mode

Figure 6

Conduction state of the control circuit in energy regenerative mode

Figure 7

Conduction state of the control circuit in energy regenerative mode

Figure 8

Fuzzy PID controller structure

Figure 9

The operating zones of the motor

Figure 10

Equivalent damping under 12V(a) and 24V(b) recovery voltage

Figure 11

Recovery power under 12V(a) and 24V(b) recovery voltage

Figure 12

Recovery efficiency under 12V(a) and 24V(b) recovery voltage

Figure 13

Comparison of ideal and actual control force in active mode(a) and energy-regenerative mode(b)

Figure 14

Comparison of dynamic performance: Body acceleration (a) time domain response and (d) frequency domain response; suspension relative displacement in (b) time domain response and (e) frequency domain; Response of dynamic tire deflection in(c) time domain and (f) frequency domain

Figure 15

(a) Instantaneous recovery power in RSAC; (b) instantaneous power consumption in ECAC