A Novel Endocrine Composite Fuzzy Control Strategy of Electromagnetic Hybrid Suspension

FARONG KOU, QIANGQIANG JING[ID], YAWEI GAO, AND JIANGHAO WU

College of Mechanical Engineering, Xi'an University of Science and Technology, Xi'an 710054, China

Corresponding author: Qiangqiang Jing (jqqedu570@163.com)

ABSTRACT To effectively improve the vehicle suspension dynamic performances, minimizing discomfort of passengers and realize vibration energy recovery, a new kind of electromagnetic hybrid suspension (EMHS) system with parallel structure of linear motor and solenoid valve shock absorber is put forward. The linear motor actuator can work at the active state for active control or energy-regenerative state for energy recovery, the solenoid valve shock absorber work at the semi-active state for damping control. Firstly, for the analysis of the hybrid suspension, a quarter dynamic model of EMHS is established. Meanwhile, the mathematical models of linear motor actuator and solenoid valve shock absorber are founded, respectively. Then, for the better suspension control effect based on fuzzy control strategy, a novel endocrine composite fuzzy control strategy is designed. By learning the biological endocrine hormone regulation mechanism, the endocrine control with long feedback and ultra-short feedback is designed. The control laws of the fuzzy controller and endocrine controller are, respectively, designed. Finally, the simulation analysis of suspension dynamic performances and energy-regenerative characteristics is done, respectively. At the same time, the bench test is carried out based on the rapid control prototype with dSPACE platform. The results show the control effect of endocrine composite fuzzy control is better than that of fuzzy control, which improves the dynamic performances. Moreover, part of vibration energy is recovered.

INDEX TERMS Electromagnetic hybrid suspension, endocrine control, fuzzy control, long feedback, ultra-short feedback.

I. INTRODUCTION

The suspension of a vehicle acts as a significant role in minimizing the shocks and vibration from the road excitation. There are basically three types of vehicle suspension system, namely passive suspension, semi-active suspension and active suspension [1], [2]. The passive suspension cannot adjust the vehicle dynamic performances, which can only support fixed damping or stiffness. Semi-active suspension can adjust the dynamic performances within the limited range, which consumes less energy. Active suspension can timely adjust the performances, but the shortage is much external energy needed than semi-active suspension.

Recently, scholars have carried out researches on how to balance the contradiction between suspension dynamic performance and energy consumption [3]–[5]. Among them,

The associate editor coordinating the review of this manuscript and approving it for publication was Kan Liu[ID].

many scholars proposed the hybrid suspension systems with hybrid actuator structure, which can work at different modes to coordinate the contradictions between dynamic performance and energy consumption. For example, in [6], a hybrid electromagnetic suspension that consists of linear motor and passive damper is proposed. Thereafter, energy regeneration, ride comfort, and driving safety are taken as control object and the effect of damping values on different control objects are studied. Finally, a bench test of 1/4 suspension is performed, and the test results verify the accuracy of the simulation results. In [7], a modified energy-saving skyhook hybrid suspension system consisting of active control and energy regeneratio is proposed, then a hybri electromagnetic actuator is designed to satisfy the control requirements. Finally, a prototype is fabricated and the bench test is conducte, the results show that the structure can satisfy the control requirement, which can coordinate the dynamic performance and energy consumption effectively.

At the same time, the control strategy has great influence on the vibration attenuation performance of hybrid suspension system. In recent years, fuzzy control has been widely studied in different control engineering areas [8], [9], especially in active or semi-active suspension control areas, due to its good robustness and strong stability [10]–[14]. However, the control laws of fuzzy control strategy are based on the experiences in a large number of experiments, and the relevant parameters in the designed fuzzy controller are fixed, so it is difficult to achieve the expected control effect, under the different external conditions. Therefore, many scholars carried out research on composite control strategies based on fuzzy control, and introduce other control strategies on the basis of fuzzy control to make better control effect [15]–[17]. Pang *et al* [18] proposed a T-S fuzzy control strategy based on fuzzy neural network, and used the structure of neural network to describe the change of the expansion factor. The simulation results show that the designed fuzzy control strategy in the variable domain could effectively improve the vehicle riding comfort and control stability. In [1], a nonlinear optimal sliding mode fuzzy control method for the active shock absorber inside the electric wheel was proposed, based on the fuzzy control theory. The comparative simulation verification was carried out, the results show that the negative effect of vertical vibration of hub motor can be effectively reduced, by the nonlinear optimal sliding mode fuzzy control of the active shock absorber in the electric wheel, which can ensure the better overall smoothness performances of the electric vehicle.

Recently, endocrine control has been widely studied in various control fields, due to its good self-learning and adaptive performance [20]–[22]. Shu *et al.* [23] proposed an intelligent controller based on neuroendocrine algorithm, and applied it to the control system of permanent magnet synchronous motor. The experiment shows that the intelligent controller has fast dynamic response, and could effectively improve the robustness of the system. Jin *et al.* [2] proposed an endocrine composite LQR control strategy for active suspension system. The results show that endocrine composite LQR control has better effect than traditional LQR control. The above research shows that endocrine control has good self-learning and adaptive performance in control engineerin, while fuzzy control strategy actuallyneeds this to achieve better control effect. At present, there is no research concerned on both fuzzy control and endocrine control. If the fuzzy control can inherit the good self-learning and adaptive performances of endocrine control when the two control strategies compound each other, then the propose composite control strategy will get better control effect than traditional fuzzy control strategy, which will propose a novel control strategy in suspension vibration control areas.

In this paper, a new kind of EMHS system with the parallel structure of linear motor and solenoid valve shock absorbe is proposed. The linear motor actuator can work at the active state or the energy-regenerative state, also, the solenoid valve shock absorber can achieve semi-active continuous damping

control. Therefore,the proposedEMHS actuator structure can work in different states, so as to recover vibration energy, while ensuring vehicle suspension dynamic performance. In Section 3, the mathematical models of EMHS actuator are founded. In section 4, anovel endocrine compositefuzzy control strategy is designe, which is combined the long feedback control and ultra-short feedback control on the basis of fuzzy control. Finally, in section 5, the simulation analysisand bench test are carried out to validate the effectiveness of proposed novel control strategy.

II. STRUCTURE AND PRINCIPLE OF EMHS SYSTEM

The structure of EMHS system is shown in Figure 1, which is mainly composed of spring, linear motor actuator, solenoid valve shock absorber, controller, battery and corresponding signal detection sensors. The linear motor actuator can choose to work in active state for active control or energy-regenerative state for energy recovery.
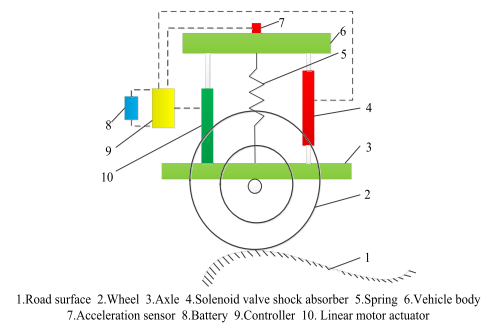
1.Road surface 2.Wheel 3.Axle 4.Solenoid valve shock absorber 5.Spring 6.Vehicle body
7.Acceleration sensor 8.Battery 9.Controller 10. Linear motor actuator

FIGURE 1. dStructure of the EMHS system.

The working principle of EMHS system is divided by different working modes of the suspension, it can work in the economy mode or sports mode. The road condition is better under the economy mode, then the solenoid valve shock absorber works in the semi-active state, outputs adjustable damping force to attenuate vibration, and the linear motor actuator works in the energy-regenerative state for energy recovery. The road condition is worse under the sports mode, then the linear motor actuator works in the active state, to output the active force for vibration attenuation. At the same time, no control current passes through the solenoid valve shock absorber, which is equivalent to the traditional hydraulic shock absorber for less energy loss.

When linear motor actuator works in the active state, the ideal force is obtained by the endocrine composite fuzzy control strategy. By inputting controllable current into the linear motor according to the ideal force, the actual force is generated to achieve vibration attenuation. When linear motor actuator works in the energy-regenerative state, by cutting the magnetic induction line, the counter electromotive force (CEMF) is generated and electric energy is stored in the super capacity, to realize the vibration energy recovery. When the solenoid valve shock absorber works in the semi-active state, the ideal force is obtained by the endocrine composite

fuzzy control strategy of the suspension controller, then the actual damping force is generated by the controllable current input according to the ideal force. The energy of active control for linear motor and semi-active control for solenoid valve shock absorber is provided by the battery.

The linear motor actuator prototype and solenoid valve shock absorber prototype are fabricated, and displayed in Figure 2.
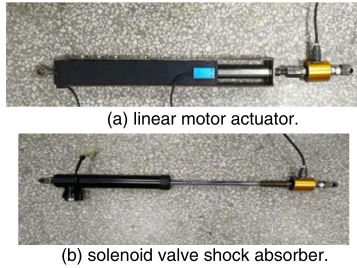

(a) linear motor actuator.

(b) solenoid valve shock absorber.

FIGURE 2. EMHS actuator Prototypes.

III. EMHS SYSTEM DYNAMIC MODEL

A. EMHS MODEL

A quarter vehicle dynamic model of EMHS system is designed as shown in Figure 3, which consists of sprung mass, unsprung mass, spring, tire and EMHS actuator. EMHS actuator includes linear motor actuator and solenoid valve shock absorber, which acts as the parallel connecting part between sprung mass and unsprung mass [25].
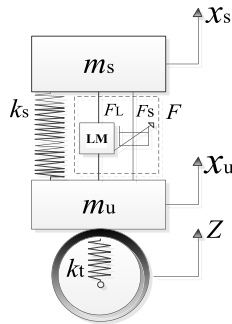

FIGURE 3. Two DOF EMHS Model.

where LM represents linear motor actuator; and SV represents solenoid valve shock absorber.

From Figure 3, based on the Newtons laws of motion, the EMHS system dynamic motion equations can be expressed as:

$$\begin{cases} m_s \ddot{x}_s + k_s(x_s - x_u) + F = 0, \\ m_u \ddot{x}_u - k_s(x_s - x_u) + k_t(x_u - z) - F = 0. \end{cases} \quad (1)$$

The state variable and output vector are selected as follows:

$$\mathbf{X} = [x_s - x_u \ \dot{x}_s \ x_u - z \ \dot{x}_u]^T,$$
$$\mathbf{Y} = [\ddot{x}_s \ x_s - x_u \ k_t(x_u - z) \ \dot{x}_u]^T,$$

where m_s is sprung mass and m_u is unsprung mass; k_s is spring stiffness coefficient and k_t is tire stiffness coefficient; F is suspension control force (especially F_L is the active force of linear motor, and F_s is the semi-active control force of solenoid valve shock absorber); Z is road input displacement; x_s is sprung mass displacement; and x_u is unsprung mass displacement.

In this way, the state-space equations of suspension can be expressed as follows:

$$\begin{cases} \dot{\mathbf{X}} = \mathbf{AX} + \mathbf{BU}, \\ \mathbf{Y} = \mathbf{CX} + \mathbf{DU}, \end{cases} \quad (2)$$

where A is state matrix; B is input matrix; C is output matrix; and D is transfer matrix. When the control input force F is 0, it becomes passive suspension.

$$\mathbf{A} = \begin{bmatrix} 0 & 1 & 0 & -1 \\ -\dfrac{k_s}{m_s} & -\dfrac{c_s}{m_s} & 0 & \dfrac{c_s}{m_s} \\ 0 & 0 & 0 & 1 \\ \dfrac{k_s}{m_u} & \dfrac{c_s}{m_u} & -\dfrac{k_t}{m_u} & -\dfrac{c_s}{m_u} \end{bmatrix},$$

$$\mathbf{B} = \begin{bmatrix} 0 & 0 \\ 0 & \dfrac{1}{m_s} \\ -1 & 0 \\ 0 & -\dfrac{1}{m_u} \end{bmatrix},$$

$$\mathbf{C} = \begin{bmatrix} -\dfrac{k_s}{m_s} & -\dfrac{c_s}{m_s} & 0 & \dfrac{c_s}{m_s} \\ 1 & 0 & 0 & 0 \\ 0 & 0 & k_t & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix}, \quad \mathbf{D} = \begin{bmatrix} 0 & \dfrac{1}{m_s} \\ 0 & 0 \\ 0 & 0 \\ 0 & 0 \end{bmatrix},$$

$$\mathbf{U} = \begin{pmatrix} \dot{z} \\ F \end{pmatrix}.$$

A filtered white noise is adopted as the road surface input model [26]:

$$\dot{z}(t) = -2\pi f_0 z(t) + 2\pi \sqrt{G_0 u_0} \omega_0(t), \quad (3)$$

where G_0 is road irregularity coefficient; f_0 is lower cutoff frequency; u_0 is vehicle speed; and ω_0 (t) is unit white noise. The different driving condition can be made up of different road irregularity and driving speed.

B. EMHS ACTUATOR MODELS

For linear motor actuator in the active state, by inputting controllable current, the active force is generated to attenuate vibration. Linear motor actuator model is obtained as follows, under the two-phase rotating d − q coordinate system [27], [28]:

$$\begin{cases} \dfrac{di_d}{dt} = -\dfrac{R}{L_d} i_d + \dfrac{L_q}{L_d} \omega i_q + \dfrac{u_d}{L_d}, \\ \dfrac{di_q}{dt} = -\dfrac{R}{L_q} i_q - \dfrac{L_d}{L_q} \omega i_d - \dfrac{\varphi_f}{L_q} \omega + \dfrac{u_q}{L_q}. \end{cases} \quad (4)$$

where R is winding resistance; L_d is direct axis inductance; L_q is quadrature axis inductance; φ_f is permanent magnet flux linkage; ω is electrical angular velocity; i_d is direct axis current; i_q is quadrature axis current; u_d is direct axis voltage; and u_q is quadrature axis voltage.

The generated active force of linear motor is expressed as:

$$F_L = 1.5 P_n \pi \varphi_f i_q / \tau, \tag{5}$$

where F_L is the active force generated by linear motor; P_n is the pole logarithm; and τ is the pole distance.

Then, the thrust coefficient of the active force for linear motor is expressed as:

$$K_i = \frac{3 P_n \pi \varphi_f}{2\tau}, \tag{6}$$

where K_i is the thrust coefficient of the active force for linear motor.

The mechanical motion equation of linear motor is expressed as:

$$M \frac{dv}{dt} = F_L - f_1 - Bv. \tag{7}$$

where M is the mass of moving parts; v is the velocity of moving parts; f_1 is the load; and B is the viscous damping coefficient.

For linear motor actuator in the energy-regenerative state, by cutting linear motor magnetic induction line[2], the CEMF is generated, then the regenerative voltage charges the super capacity, the regenerative voltage is expressed as:

$$U_r = K_e \dot{x}_{s-u}, \tag{8}$$

where U_r is the regenerative voltage; $\dot{x}_{s-u}$ is the suspension velocity; and K_e is the CEMF coefficient of linear motor.

The regenerative power of linear motor is used, to represent the energy-regenerative characteristics of EMHS system, which is expressed as:

$$P_r = U_r \cdot i_r = \frac{U_r^2}{R}. \tag{9}$$

where P_r is the regenerative power of linear motor; and i_r is the coil current of linear motor in energy-regenerative state.

For solenoid valve shock absorber in the semi-active state, the normally close structure type is chose, and the solenoid valve shock absorber model is built through test modelling in Figure 4. The solenoid valve shock absorber installed on the test-bed, the sinusoidal excitation of frequency is at 2Hz and the amplitude is at 5mm from vibration table, is taken as road input. The regulated DC power supplies adjustable current to the solenoid valve shock absorber, then the damping force and suspension displacement signals are measured by force sensor and displacement sensor, respectively. The collected signals are processed by data acquisition instrument. Finally, under various control currents, the regression fitting curves of velocity characteristics for solenoid valve shock absorber, are shown in Figure 5.
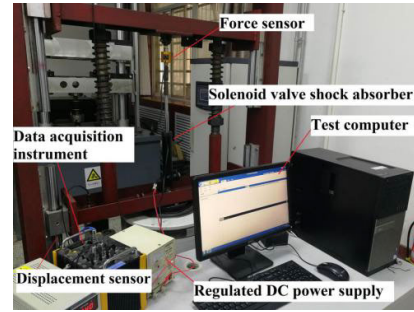

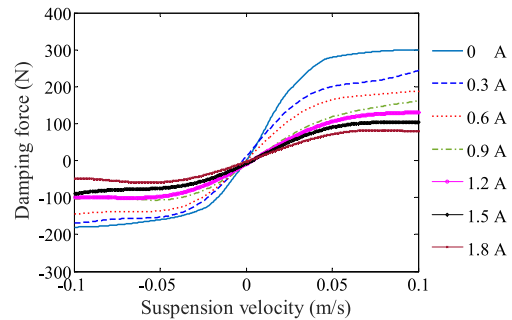**FIGURE 4.** Test modelling of solenoid valve shock absorber.

FIGURE 5. Regression fitting curves oftest modelling.

Then, the damping force F_s of solenoid valve shock absorber is expressed as:

$$F_s = \sum_{k=0}^{3} (b_k I^2 + c_k I + d_k)\dot{x}_{s-u}{}^k, \tag{10}$$

where k is 0, 1, 2, 3; b_k, c_k and d_k are polynomial coefficients; and I is control current of solenoid valve shock absorber.

The regression analysis is taken to identify the polynomial model parameters, and the identified resultsare as shown in Table 1. Finally, the polynomial model can be obtained by taking the identified parameters results into equation (10).

TABLE 1. Parameter identification results.

k	0	1	2	3
b_k	9614	8905	-81.0	-11.45
c_k	26240	-18980	-894.1	10.16
d_k	-95216	17288	2420.3	1.86

IV. ENDOCRINE COMPOSITE FUZZY CONTROL STRATEGY DESIGN

For better control effect of EMHS system,a novel Endocrine composite fuzzy control strategy is proposed, which is composed of endocrine control and fuzzy control. By learning the endocrine regulation mechanism of biological hormone, the designed endocrine control includes long feedback

control unit and ultra-short feedback control unit. The EMHS system control block diagram is shown in Figure 6.
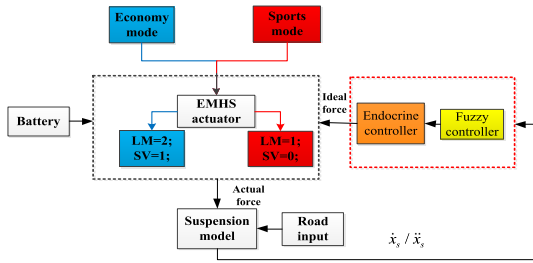

FIGURE 6. Control block diagram of EMHS system.

From Figure 6, LM = 1 represents the active state of linear motor, LM = 2 represents the energy-regenerative state of linear motor. SV = 0 represents that solenoid valve shock absorber acts as the ordinary hydraulic shock absorber with no current; SV = 1 represents the semi-active state of solenoid valve shock absorber.

Under the better driving conditions with better road surface level and lower vehicle speed, the EHMS system is selected to work in the economy mode, then the solenoid valve shock absorber works in the semi-active state, to generate damping force for attenuate vibration. The solenoid valve shock absorber can achieve better vibration attenuation control effect with less energy consumption in the semi-active state. Meanwhile, the linear motor actuator choose to work in the energy-regenerative state, to recover vibration energy.

Under the worse driving conditions with worse road surface level and higher vehicle speed, the vibration attenuation comes first place, then the EMHS system is selected to work in the sports mode. The vibration attenuation effect of linear motor actuator in the active state is better than the semi-active state of the solenoid valve shock absorber, cause the linear motor has a larger output power. Hence, the linear motor is selected to work in the active state, to generate the active force for vibration attenuation. The solenoid valve shock absorber is not energized, which acts as the ordinary hydraulic shock absorber to reduce the energy consumption.

A. STRUCTURE OF ENDOCRINE COMPOSITE FUZZY CONTROL STRATEGY

The endocrine composite fuzzy control strategy is based on the mechanism of hormone feedback regulation [30], [31]. The endocrine hormone regulating system makes up of the hypothalamus, pituitary and endocrine glands. The specific process of hormone regulation is as follows:

Firstly, the regulation loop contains positive feedback regulation and negative feedback regulation, the positive feedback regulation is from hypothalamus to endocrine gland, on the contrary, the negative feedback regulation is from endocrine gland to hypothalamus. In the positive feedback regulation, the hypothalamus secreted pituitary hormone H1, then H1 stimulates the pituitary to secrete the

endocrine gland stimulating hormone H2, which in turn stimulates the endocrine glands to produce the corresponding hormone H3.

In the negative feedback regulation, the concentration of hormone H3 comes too high, which in turn acts on the hypothalamus and pituitary gland to inhibit the secretion of corresponding hormones.The positive and negative feedback regulation of hormone H3 on the hypothalamus and pituitary forms long feedback loop.

Otherwise, the gland stimulating hormone H2 released by the pituitary not only affects the endocrine glands, but also affects the pituitary itself, forming ultra-short feedback loop. The working principle is shown in Figure 7.
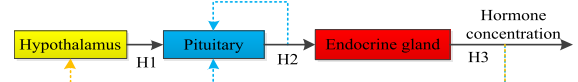

FIGURE 7. Hormone regulation loop of endocrine system.

In view of the above regulating mechanism, the proposed control structure is shown in Figure 8, which is composed of the fuzzy controller and endocrine controller. The endocrine controller includes the long feedback control unit and the ultra-short feedback control unit, the long feedback control unit consists of the primary control unit and the secondary control unit.
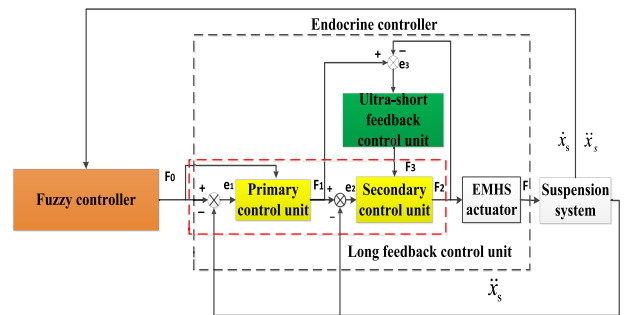

FIGURE 8. Control structure block diagram of endocrine composite fuzzy.

where F_0 is the output ideal force from the fuzzy controller; F_1 is the output control force of primary control unit; F_2 is the output control force of secondary control unit; F_3 is the output control force of ultra-short feedback control unit; F is the output control force of EMHA actuator; e_1, e_2, and e_3 are the output deviation signals of primary control unit, secondary control unit and ultra-short feedback control unit, respectively; $\dot{x}_s$ is the sprung mass velocity; and $\ddot{x}_s$ is the sprung mass acceleration.

The primary control unit and the secondary control unit simulate the hypothalamus and pituitary, in the endocrine controller, respectively. The direct feedback index is sprung mass acceleration. The ultra-short feedback control unit simulates the ultra-short feedback loop in the biological endocrine system.

B. ENDOCRINE COMPOSITE FUZZY CONTROLLER DESIGN

The endocrine composite fuzzy controller consists of fuzzy controller and endocrine controller. The output force of the fuzzy controller and the sprung mass acceleration feedback of EMHS system, are used as the input of the endocrine controller.

1) FUZZY CONTROLLER DESIGN

The two variables input and single variable output structure of the fuzzy controller is designed. The main evaluation index is sprung mass in suspension control area, s he sprung mass acceleration and its changing rate are used as input variables, to design the fuzzy controller. Seven language sets are used to describe the fuzzy state of input variables and output variables [32]–[34]. The seven specific language sets are named {negative big, negative medium, negative small, zero, positive small, positive medium and positive big}, the short form of them is {NB NM NS ZE PS PM PB}, respectively.

The basic fuzzy domain of sprung mass acceleration (E used to represent) and its changing rate (Ec used to represent) are set as $[-6 \ 6]$. The basic fuzzy domain of output variable (u used to represent) is set as $[-7, 7]$. When the basic fuzzy domain is determined, the membership function of fuzzy language variables, which is called the assignment of fuzzy variables, should be determined according to the actual situation. Fuzzy language is finally described by membership function. Generally speaking, the steeper the shape of the membership function, the higher the resolution and the higher the control sensitivity. On the contrary, if the membership function changes slowly, the control characteristics are relatively gentle and the stability of the system is relatively good. Therefore, in the selection of membership functions, the membership functions with higher resolution are generally adopted in the regions near the zero error, while in the regions with greater error, the membership functions with lower resolution can always be adopted in order to make the system have good robustness. The triangle membership function is simple, and can satisfy the control precision of general control system, so thegeneral triangle function is used for the membership function of input and output variables, mamdani method is used for fuzzy reasoning, and centroid method is used for fuzzy solving. Fuzzy rules use language to specifically describe the relationship between input and output variables. Whether the rules are reasonable or not directly affects the vibration attenuation effect of EMHS system. Finally, the specific fuzzy rules are shown in Table 2.
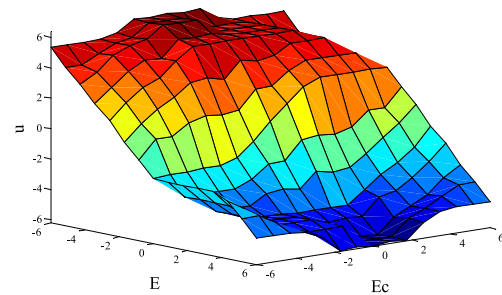
The input and output surface of the fuzzy control system is finally shown in Figure 9.

2) ENDOCRINE CONTROLLER DESIGN

By learning from the biological hormone feedback regulation, the designed endocrine controller makes up of long feedback and ultra-short feedback control unit, especially long feedback control unit consists of primary control unit and secondary control unit. The designed control law of each unit is as follows.

TABLE 2. Rules of fuzzy control.

E \ Ec	NB	NM	NS	ZE	PS	PM	PB
NB	PM	PM	PB	PB	PB	PM	PM
NM	PS	PM	PB	PB	PM	PM	PS
NS	ZE	PS	PM	PM	PM	PM	PS
ZE	NS	NS	NS	ZE	PS	PS	PS
PS	NS	NM	NM	NM	NM	NS	ZE
PM	NS	NM	NM	NB	NB	NM	NS
PB	NM	NM	NB	NB	NB	NM	NM

FIGURE 9. Input and output surface of fuzzy inference system.

a: LONG FEEDBACK CONTROL LAW

For the primary control, the proportional adjustment can easily reach a stable state, the output control force F_1 is expressed as:

$$F_1 = F_0 + K_1 e_1 \tag{11}$$

The deviation signal e_1 of the primary control unit is expressed as:

$$e_1 = F_0 - \ddot{x}_s, \tag{12}$$

The deviation signal e_3 of the ultra-short feedback control unit is expressed as:

$$e_3 = F_2 - F_1, \tag{13}$$

where K_1 is the proportional coefficient of the primary control unit; and F_0 is the output ideal force of different modes from the fuzzy controller.

The PID control is taken for secondary control unit, the output control force F_2 is expressed as:

$$F_2 = K_p e_2 + K_i \int e_2 dt + K_d \frac{de_2}{dt} + F_3, \tag{14}$$

where F_3 is the output force of ultra-short feedback control unit.

The deviation signal e_2 for the secondary control unit is as follows:

$$e_2 = F_1 - \ddot{x}_s, \qquad (15)$$

where K_P, K_i and K_d are the proportional coefficient, integral coefficient and differential coefficient of PID control, respectively.

b: ULTRA-SHORT FEEDBACK CONTROL LAW
The ultra-short feedback control adopts the endocrine regulation law, the output changing rate of the secondary control unit is taken as the input signal of the ultra-short feedback unit. According to the general rule of endocrine hormones proposed in literature [35], the control variable is ultra-short feedback processed, and the nonlinear feedback function is obtained as follows:

$$F_3 = bc\left\{\frac{[\Delta F_2(k)]^n}{1+[\Delta F_2(k)]^n}\right\} \qquad (16)$$

$$b = \begin{cases} +1 & e_2 \geq 0 \\ -1 & e_2 \leq 0 \end{cases} \qquad (17)$$

where cn is the factor coefficient, which determines the amplitude of ultra-short feedback compensation; b is the constant coefficient, which determines the direction of ultra-short feedback compensation, and the choice is enhancement or inhibition.

The changing rate of the secondary control unit is selected as the ultra-short feedback input signal. Finally, the output of the secondary control unit after the ultra-short feedback unit is considered as follows:

$$F_2 = K_p e_2 + K_i \int e_2 dt + K_d \frac{de_2}{dt} + bc\left\{\frac{[\Delta F_2(k)]^n}{1+[\Delta F_2(k)]^n}\right\}, \qquad (18)$$

V. ANALYSIS AND BENCH TEST
In order to verify the effectiveness of the endocrine composite fuzzy control strategy of the EMHS system, the simulation analysis of the random road was carried out with passive suspension, fuzzy control strategy and endocrine composite fuzzy control strategy, respectively. Also, the energy-regenerative characteristic analysis was carried out. The road conditions under economy mode and sports mode are with different vehicle speed and road surface level, the specific parameters about road conditions as shown in the Table 3 below.

TABLE 3. Driving conditions.

Modes	Vehicle speed (km/h)	Road level
Economy	30	B
Sports	60	C

The corresponding road input displacement is shown in Figure 10.
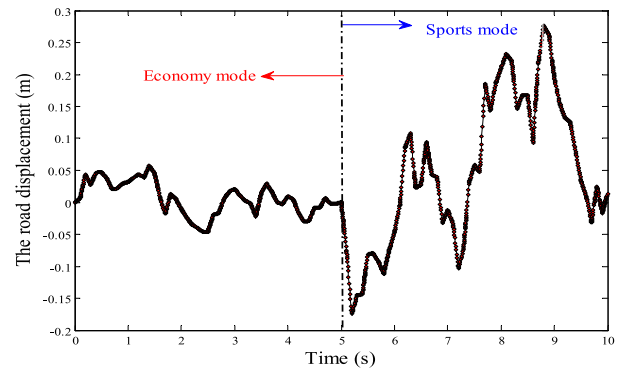
FIGURE 10. Corresponding road input displacement in different modes.

The specific suspension system parameters are shown in Table 4 below.

TABLE 4. Vehicle parameters.

Vehicle parameters	Values
Sprung mass (kg)	280
Unsprung mass (kg)	27
Tire stiffness coefficient (N/m)	150000
Spring stiffness coefficient (N/m)	12000
Thrust coefficient of linear motor (N/A)	78.54
CEMF coefficient of linear motor (V·S·m^{-1})	68.42
Winding resistance of linear motor (Ω)	10.1
Lower cutoff frequency (Hz)	0.1

The parameters of endocrine controller of different modes are finally shown in Table 5 after the adjustment.

TABLE 5. Endocrine composite fuzzy controller parameters.

Working modes	Parameters					
	K_1	K_p	K_i	K_d	c	n
Economy mode	2.52	0.36	0.00048	0.000012	1	2
Sports mode	2.65	0.36	0.00068	0	1	2

A. SIMULATION ANALYSIS
The simulation analysis in time domain and frequency domain of the passive suspension, the suspension with fuzzy control strategy and the suspension with endocrine composite fuzzy control strategy, are respectively carried out. Also, the energy-regenerative characteristics are analyzed.

1) TIME DOMAIN ANALYSIS
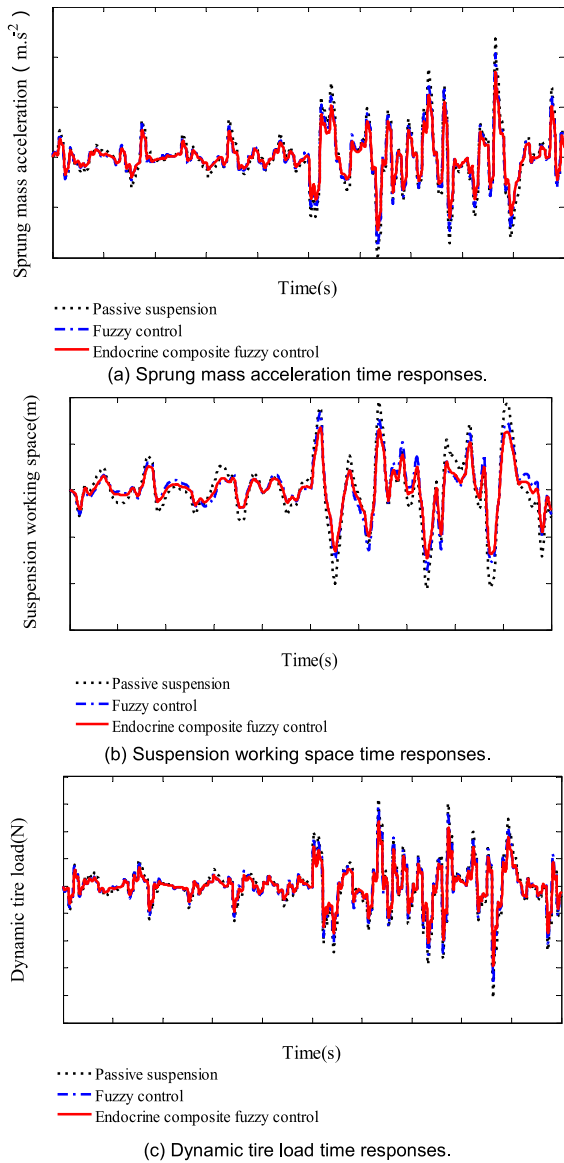Finally, the time domain responses of sprung mass acceleration, suspension working space and dynamic tire load of all

FIGURE 11. The suspension time domain responses.

FIGURE 12. The suspension frequency domain responses.

types of suspension, under different modes, are obtained as shown in Figure 11. The root mean square (RMS) values of dynamic performance indexes and control effect of all types of suspension, are as shown in Table 6.

In order to clearly compare the control effects, the RMS values of all indexes are shown in Table 6.

It can be seen from Figure 11 and Table 6, the fuzzy control and endocrine composite fuzzy control greatly improve the vehicle dynamic performances compared with passive suspension, and the control effect of endocrine composite fuzzy control is superior to the fuzzy control under different modes. For example, under the economy mode, the sprung mass acceleration, suspension working space and the dynamic tire load are respectively reduced by 10.1%, 9.8% and 9.9% with fuzzy control, compared with the passive suspension. The same indexes with endocrine composite fuzzy control are
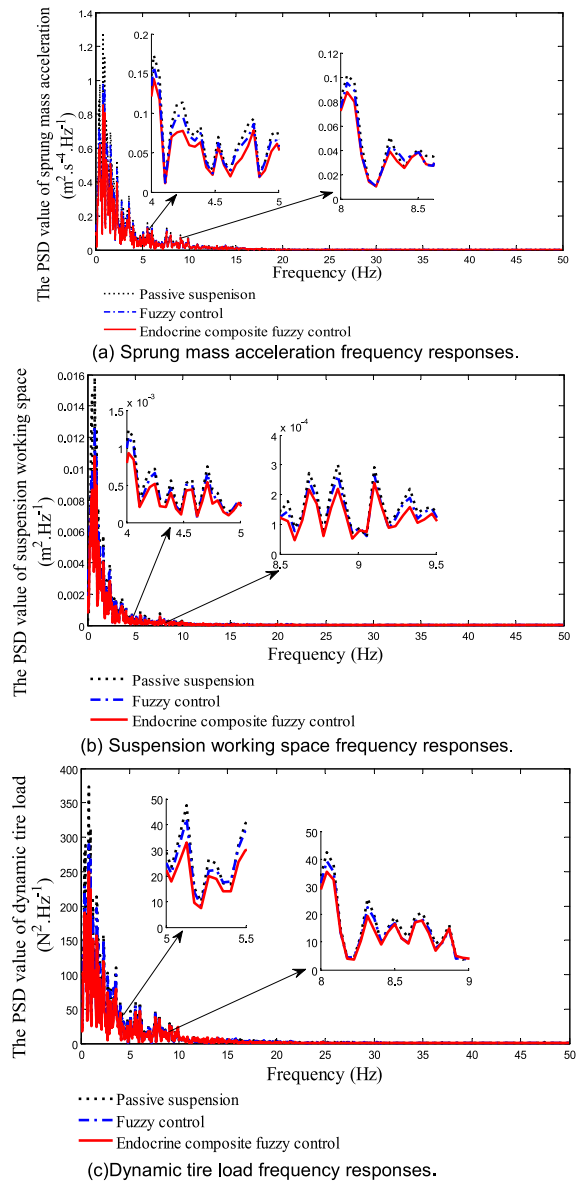
respectively reduced by 18.9%, 13.8% and 19.1%. Under the sports mode, the sprung mass acceleration, suspension working space and the dynamic tire load are respectively reduced by 20%, 24.5% and 17.5% with fuzzy control. The same indexes are respectively reduced by 31.4%, 27.9% and 31.1% with endocrine composite fuzzy control. It can be seen that, endocrine composite fuzzy control get better control effect than fuzzy control, which effectively improves vehicle riding comfort and handling stability.

2) FREQUENCY DOMAIN ANALYSIS
In order to analyze the control effects of each strategy, from the perspective of frequency domain, the power spectral density (PSD) responses of all indexes are shown in Figure 12. The highest peak values in the frequency bands are quantified,

TABLE 6. RMS values of time domain responses of each index.

Modes	Indexes	Suspension Type			Control effect（%）	
		Passive suspension	Fuzzy control	Endocrine composite fuzzy control	Fuzzy control	Endocrine composite fuzzy control
Economy	$a(m \cdot s^{-2})$	1.0455	0.9409	0.8479	-10.1	-18.9
	SWS(m)	0.0133	0.0120	0.0114	-9.8	-13.8
	DTL(N)	313.68	282.32	253.77	-9.9	-19.1
Sports	$a(m \cdot s^{-2})$	2.9544	2.363	2.0267	-20	-31.4
	SWS(m)	0.0370	0.028	0.0267	-24.5	-27.9
	DTL(N)	897.07	740.26	618.09	-17.5	-31.1

TABLE 7. The highest peak values quantification and control effect of the PSD value for different suspensions.

Indexes	Suspension Type			Control effect（%）	
	Passive suspension	Fuzzy control	Endocrine composite fuzzy control	Fuzzy control	Endocrine composite fuzzy control
$a((m \cdot s^{-2})^2 \cdot Hz^{-1})$	1.283	0.977	0.853	-23.8	-33.5
$SWS(m^2 \cdot Hz^{-1})$	0.0158	0.0127	0.0108	-19.6	-31.6
$DTL(N^2 \cdot Hz^{-1})$	373.9	289.3	249.5	-22.6	-33.3

and the reduction degree of the highest peak values is taken as the evaluation standard of the frequency domain analysis. The results are shown in Table 7.

It can be seen from Figure 12 and Table 7, the fuzzy control and endocrine composite fuzzy control greatly improve the vehicle dynamic performances compared with passive suspension, and the control effect of endocrine composite fuzzy control is superior to the fuzzy control in frequency domain. For example, the sprung mass acceleration, suspension working space and the dynamic tire load are respectively reduced by 23.8%,19.6% and 22.6% with fuzzy control, compared with the passive suspension. The same indexes with endocrine composite fuzzy control are respectively reduced by 33.5%,31.6% and 33.3%. It can be seen that, endocrine composite fuzzy control get better control effect than fuzzy control, which effectively improves vehicle riding comfort and handling stability.

3) ENERGY-REGENERATIVECHARACTERISTI

The energy-regenerative characteristic of EMHS system is expressed by the regenerative power of linear motor, which is shown in Figure 13.

Passive suspension cannot regenerate energy, only the designed EMHS suspension system with fuzzy control or endocrine composite fuzzy control can regenerate energy under the economy mode. Figure 13 shows the energy-regenerative characteristic of fuzzy control and endocrine composite fuzzy control. It can been seen that the linear motor is in the energy-regenerative state during 0-5s. Combing with the road input displacement in Figure 10, it can be known that, this period is under economy mode. When the EMHS system
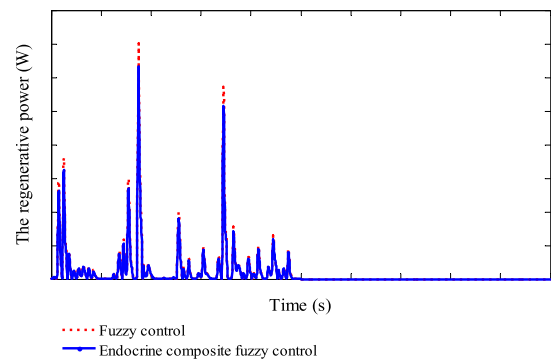

FIGURE 13. The regenerative power.

works at the economy mode, the damping force is outputted by solenoid valve shock absorber, and the linear motor is in the energy-regenerative state. Figure 13 shows that the peak value of regenerative power with two control strategies is almost to 35W, the difference value of average regenerative voltage is within 3.5%. These two control strategies have little difference in energy-regenerative effects.

B. BENCH TEST

In order to verify the simulation results of the designed endocrine composite fuzzy control strategy, the bench test is carried out based on the rapid control prototype with dSPACE platform. The bench test system mainly includes designed endocrine composite fuzzy controller, the EMHS system composed of linear motor actuator and solenoid valve shock absorber, ESG-62 vibration table to simulate road excitation input, acceleration sensor, and DH5902 data acquisition instrument for signal acquisition.

The designed endocrine composite fuzzy suspension controller model was imported into the dSPACE platform, and the ControlDesk software of dSPACE platform was used to configure IO port. Also, the dSPACE platform was connected with the inverter or energy-regenerative circuit. The EMHS actuator can output the control force for vibration attenuation or recover the energy. The structure of the bench test is shown in Figure 14.
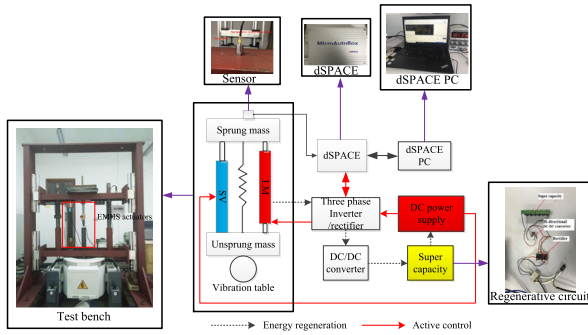

FIGURE 14. Structure of the bench test.

The endocrine composite fuzzy control of EMHS system was tested and compared with the simulation results. With the limitation of test conditions, only sprung mass acceleration was detected, the time domain response results of sprung mass acceleration of the EMHS system are shown in Figure15, and the relative error with test result and simulation result is shown in Figure 16.
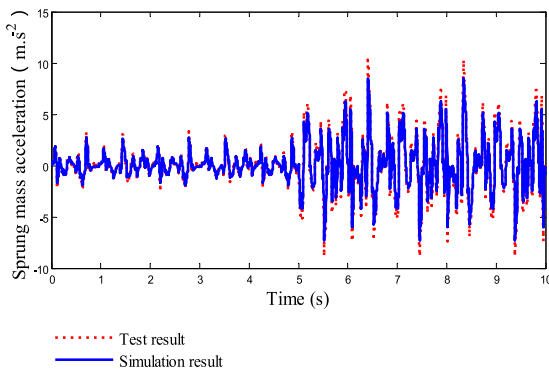
FIGURE 15. Test result of sprung mass acceleration in time domain.

From Figure 15, the test results are basically consistent with simulation results. In Figure 16, the relative error between them is from 2%-4%, which is within the acceptable rang. The test results has validated the accuracy of simulation results. Under economy mode, road condition is better, so the relative error is less. Under sports mode, road condition is worse, so the relative error is greater. The error is mainly contributed for two reasons. On the one hand, accuracy error between the mathematical modeling of the EMHS actuator in the simulation and the actual actuator prototype exists. On the other hand, more vibration noise and interfere exists in the actual test, worse road condition leads more noise and
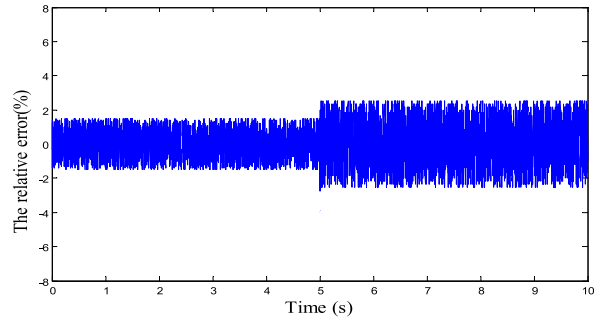

FIGURE 16. The relative error of test and simulation result.

interfere, also, the measuring instruments exists measuring errors, which finally lead the error between the simulation results and test results.

The frequency domain of sprung mass acceleration is shown in Figure 17, the test result and simulation result are basically consistent, the peak values for test result are little bigger. The main reason for the error is the simulation condition is much more ideal, the vibration noise exists in test condition, also, the filtering error exists in data acquisition.
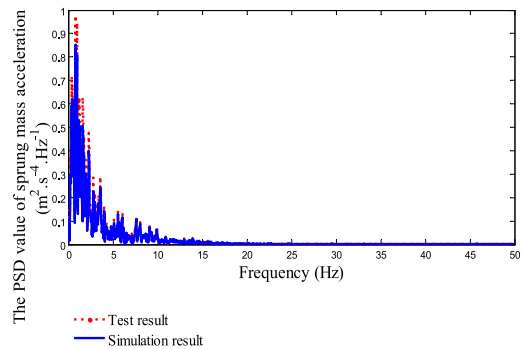

FIGURE 17. Test result of sprung mass acceleration in frequency domain.

Figure 18 shows the comparison of regenerative power between test result and simulation result, there is little difference between them overall. As for the peak values, test result is little bit lower than simulation result. The main reason for the difference is losses of the electronic components of the energy-regenerative circuit.
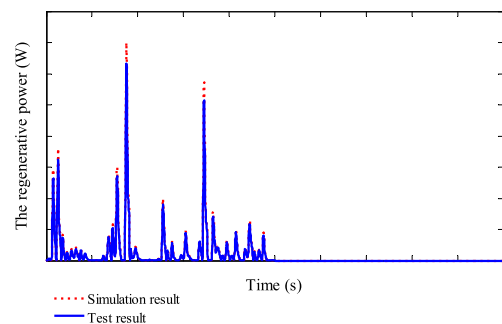

FIGURE 18. Test result of regenerative power.

VI. CONCLUSION

In this paper, a new kind of EMHS system is put forward, which is based on the actuator wit the parallel structure of linear motor and solenoid valve shock absorber. The mathematical models of linear motor are founded, both in the active and energy-regenerative state. Meanwhile, the velocity characteristic tests of solenoid valve shock absorber are carried out, to obtain the polynomial mathematical model in the semi-active state. The EMHS actuator can work in the different states under different modes.

For better control effect, the endocrine control with long feedback and ultra-short feedback is proposed, then a novel endocrine composite fuzzy control strategy is designed. Simulation analysis and bench test are carried out, to validate the control effect of endocrine composite fuzzy control strategy. The results show that the proposed endocrine composite fuzzy control get better control effect than traditional fuzzy control. For example, under the sports mode, the sprung mass acceleration, suspension working space and the dynamic tire load are respectively reduced by 20%, 24.5% and 17.5% with fuzzy control. The same indexes are respectively reduced by 31.4%, 27.9% and 31.1% with endocrine composite fuzzy control. Meanwhile, under the economy mode, part of vibration energy is recovered while the vehicle dynamic performance is guaranteed, and little difference about energy-regenerative characteristic of fuzzy control and endocrine composite fuzzy control. The future works include:1) Designing and manufacturing the integrated EMHS actuator so as to reduce actual installation space; 2) Optimization and improvement of endocrine control law to get better control effect.

FUNDING

CONFLICTS OF INTEREST

The authors declare that there are no conflicts of interest.

REFERENCES

[1] H. E. Tseng and D. Hrovat, "State of the art survey: Active and semi-active suspension control," *Vehicle Syst. Dyn.*, vol. 53, no. 7, pp. 1034–1062, 2015, doi: 10.1080/00423114.2015.1037313.

[2] D. Ning, S. Sun, H. Du, W. Li, and W. Li, "Control of a multiple-DOF vehicle seat suspension with roll and vertical vibration," *J. Sound Vib.*, vol. 435, pp. 170–191, Nov. 2018, doi: 10.1016/j.jsv.2018.08.005.

[3] Y. Suda, S. Nakadai, and K. Nakano, "Hybrid suspension system with skyhook control and energy regeneration (development of self-powered active suspension)," *Vehicle Syst. Dyn.*, vol. 29, no. 1, pp. 619–634, 1998, doi: 10.1080/00423119808969590.

[4] B. Ebrahimi, H. Bolandhemmat, M. B. Khamesee, and F. Golnaraghi, "A hybrid electromagnetic shock absorber for active vehicle suspension systems," *Vehicle Syst. Dyn.*, vol. 49, nos. 1–2, pp. 311–332, 2011, doi: 10.1080/00423111003602400.

[5] F. Kou, J. Du, Z. Wang, D. Li, and J. Xu, "Nonlinear modeling and coordinate optimization of a semi-active energy regenerative suspension with an electro-hydraulic actuator," *Algorithms*, vol. 11, no. 2, pp. 1–17, 2018, doi: 10.3390/a11020012.

[6] R. Wang, R. Ding, and L. Chen, "Application of hybrid electromagnetic suspension in vibration energy regeneration and active control," *J. Vib. Control*, vol. 24, no. 1, pp. 223–233, Jan. 2018, doi: 10.1177/1077546316637726.

[7] R. Ding, R. Wang, X. Meng, and L. Chen, "A modified energy-saving skyhook for active suspension based on a hybrid electromagnetic actuator," *J. Vib. Control*, vol. 25, no. 2, pp. 286–297, 2018, doi: 10.1177/1077546318775508.

[8] Y. Sun, J. Xu, H. Qiang, and G. Lin, "Adaptive neural-fuzzy robust position control scheme for maglev train systems with experimental verification," *IEEE Trans. Ind. Electron.*, vol. 66, no. 11, pp. 8589–8599, Nov. 2019, doi: 10.1109/tie.2019.2891409.

[9] Y. Sun, H. Qiang, J. Xu, and G. Lin, "Internet of Things-based online condition monitor and improved adaptive fuzzy control for a medium-low-speed maglev train system," *IEEE Trans. Ind. Informat.*, vol. 16, no. 4, pp. 2629–2639, Apr. 2020, doi: 10.1109/tii.2019.2938145.

[10] J. Lin and Y. B. Zheng, "Vibration suppression control of smart piezoelectric rotating truss structure by parallel neuro-fuzzy control with genetic algorithm tuning," *J. Sound Vib.*, vol. 331, no. 16, pp. 3677–3694, Jul. 2012, doi: 10.1016/j.jsv.2012.04.001.

[11] J. Fu, J. Bai, J. Lai, P. Li, M. Yu, and H.-K. Lam, "Adaptive fuzzy control of a magnetorheological elastomer vibration isolation system with time-varying sinusoidal excitations," *J. Sound Vib.*, vol. 456, pp. 386–406, Sep. 2019, doi: 10.1016/j.jsv.2019.05.046.

[12] J. Yang, M. Zha, L. Xie, and X. E. Tian, "Multi-sensors-based security control for T-S fuzzy systems over resource-constrained networks," *J. Franklin Inst.*, vol. 357, pp. 4286–4315, May 2020, doi: 10.1016/j.jfranklin.2020.01.017.

[13] B.-P. Huynh and Y.-L. Kuo, "Optimal fuzzy impedance control for a robot gripper using gradient descent iterative learning control in fuzzy rule base design," *Appl. Sci.*, vol. 10, no. 11, pp. 3821–3837, 2020, doi: 10.3390/app10113821.

[14] J. Saransh, S. Shubham, I. P. Catalin, and R. U. Deepak, "Performance investigation of integrated model of quarter car semi-active seat suspension with human model," *Appl. Sci.*, vol. 10, no. 9, pp. 3185–3203, 2020, doi: 10.3390/app10093185.

[15] J. Liu, X. Li, Z. Wang, and Y. Zhang, "Modelling and experimental study on active energy-regenerative suspension structure with variable universe fuzzy PD control," *Shock Vib.*, vol. 2016, pp. 1–11, Nov. 2016, doi: 10.1155/2016/6170275.

[16] D. X. Phu and S.-B. Choi, "A new adaptive fuzzy PID controller based on Riccati-like equation with application to vibration control of vehicle seat suspension," *Appl. Sci.*, vol. 9, no. 21, pp. 4540–4555, 2019, doi: 10.3390/app9214540.

[17] C. Chen, J. Xu, G. Lin, Y. Sun, and D. Gao, "Fuzzy adaptive control particle swarm optimization based on T-S fuzzy model of maglev vehicle suspension system," *J. Mech. Sci. Technol.*, vol. 34, no. 1, pp. 43–54, Jan. 2020, doi: 10.1007/s12206-019-1247-4.

[18] H. Pang, F. Liu, and Y. Wang, "Fuzzy control in the variable field of magnetorheological semi-active suspension of a cross-country vehicle," (in Chinese), *J. Vib.*, vol. 39, no. 2, pp. 311–319 and 443–444, 2019, doi: 10.16450/j.cnki.issn.1004-6801.2019.02.013.

[19] J. C. Wang and R. He, "Nonlinear optimal sliding mode fuzzy control for active shock absorber in electric wheel," *Automot. Eng.*, vol. 40, no. 6, pp. 719–725, 2018, doi: 10.19562/j.chinasae.qcgc.2018.06.015.

[20] C. Sauze and M. Neal, "Artificial endocrine controller for power management in robotic systems," *IEEE Trans. Neural Netw. Learn. Syst.*, vol. 24, no. 12, pp. 1973–1985, Dec. 2013, doi: 10.1109/tnnls.2013.2271094.

[21] M. B. Milovanović, D. S. Antić, M. T. Milojković, S. S. Nikolić, S. L. Perić, and M. D. Spasić, "Adaptive PID control based on orthogonal endocrine neural networks," *Neural Netw.*, vol. 84, pp. 80–90, Dec. 2016, doi: 10.1016/j.neunet.2016.08.012.

[22] X. Liang, Y. Ding, L. Ren, K. Hao, and Y. Jin, "Data-driven cooperative intelligent controller based on the endocrine regulation mechanism," *IEEE Trans. Control Syst. Technol.*, vol. 22, no. 1, pp. 94–101, Jan. 2014, doi: 10.1109/tcst.2013.2245417.

[23] S. Shu, X. Wang, H. Xia, and C. Yu, "Design of intelligent controller based on neuroendocrine algorithm," (in Chinese), *J. Electron. Meas. Instrum.*, vol. 32, no. 7, pp. 192–197, 2018, doi: 10.13382/j.jemi.2018.07.028.

[24] Y. Jin, D. Yu, Z. Chen, M. Jiang, and X. He, "Endocrine LQR control strategy and active suspension vibration reduction research," (in Chinese), *J. Vib. Shock*, vol. 35, no. 10, pp. 49–54, 2016, doi: 10.13465/j.cnki.jvs.2016.10.008.

[25] G. Geng, Y. Yu, L. Sun, and H. Li, "Research on ride comfort and driving safety under hybrid damping extension control for suspension systems," *Appl. Sci.*, vol. 10, no. 4, pp. 1442–1466, 2020, doi: 10.3390/app10041442.

[26] R. Ding, R. Wang, X. Meng, and L. Chen, "Energy consumption sensitivity analysis and energy-reduction control of hybrid electromagnetic active suspension," *Mech. Syst. Signal Process.*, vol. 134, Dec. 2019, Art. no. 106301, doi: 10.1016/j.ymssp.2019.106301.

[27] J. Si, H. Wang, X. Xu, and H. Feng, *Modeling, Characteristic Analysis and Thrust Control of PMLSM*. Beijing, China: China Univ. of Mining and Technology Press, (in Chinese), 2014, ch. 8, sec. 4, pp. 185–195.

[28] J. Wang, W. Wang, and K. Atallah, "A linear permanent-magnet motor for active vehicle suspension," *IEEE Trans. Veh. Technol.*, vol. 60, no. 1, pp. 55–63, Jan. 2011, doi: 10.1109/TVT.2010.2089546.

[29] A. Thul, D. Eggers, B. Riemer, and K. Hameyer, "Active suspension system with integrated electrical tubular linear motor: Design, control strategy and validation," *Arch. Electr. Eng.*, vol. 64, no. 4, pp. 605–616, Dec. 2015, doi: 10.1515/aee-2015-0045.

[30] A. J. Tiblbrook and I. J. Clarke, "Neuroendocrine mechanisims of innate states of attenuated responsiveness of the hypothalamo-pituitary adrenal axis to stress," *Frontiers Neuroendocinol.*, vol. 27, no. 3, pp. 285–307, 2006.

[31] F. Kou, Q. Jing, C. Chen, and J. Wu, "Endocrine composite skyhook-groundhook control of electromagnetic linear hybrid active suspension," *Shock Vib.*, vol. 2020, pp. 1–17, Feb. 2020, doi: 10.1155/2020/3402168.

[32] T. Xue, W. Li, Y. F. Du, E. R. Mao, and H. J. Wen, "Adaptive fuzzy sliding mode control for active suspension of high altitude gap sprayer," (in Chinese), *J. Agricult. Eng.*, vol. 34, no. 21, pp. 47–56, 2018.

[33] M. Yu, C. Y. Zhou, L. Wei, X. Zhao, and Q. Yu, "H$_\infty$ control of vehicle electro-hydraulic suspension system based on T-S fuzzy model," (in Chinese), *China J. Highway Transp.*, vol. 31, no. 8, pp. 205–217, 2018.

[34] H. Pang, J. Liang, J. P. Wang, and F. Liu, "Adaptive fuzzy sliding mode control for vehicle active suspension considering system uncertainty," (in Chinese), *J. Vib. Shock*, vol. 37, no. 15, pp. 261–269, 2018, doi: 10.1.3465/j.cnki.jvs.2018.15.036.

[35] M. Zhao, J. H. Ye, C. J. Li, and P. F. Chen, "Voltage regulator control based on endocrine single neuron sliding mode in nuclear power plant," (in Chinese), *J. Chin. Soc. Power Eng.*, vol. 37, no. 7, pp. 552–557, 2017.

FARONG KOU born in Gansu, China. He received the master's degree from Chang'an University, in 2003, and the Ph.D. degree from Northwest Polytechnic University, in 2008. He has been a Professor of mechanical engineering with the School of Xi'an University of Science and Technology, since 2017, and has published more than 60 articles and more than 70 invention patents, mainly engaged in vehicle dynamics research.

QIANGQIANG JING born in Shaanxi, China. He received the bachelor's degree from the Xi'an University of Science and Technology, in 2018, where he is currently pursuing the master's degree, mainly engaged in vehicle dynamics research, especially in active suspension control area.

YAWEI GAO born in Shanxi, China. He received the bachelor's degree from North China University, in 2018. He is currently pursuing the master's degree with the Xi'an University of Science and Technology, mainly engaged in vehicle dynamics research.

JIANGHAO WU born in Shanxi, China. He received the bachelor's degree from the Xi'an University of Science and Technology, in 2019, where he is currently pursuing the master's degree, mainly engaged in vehicle dynamics research.

● ● ●