Intelligent Control of Vehicle Magneto-Rheological Semi-Active Suspension

Quanmin Guo[1, 2]

[1] School of Mechanical and Precision Instrument Engineering,
Xi'an University of Technology, Xi'an 710048, Shaanxi, China
[2] School of Electronic Information Engineering,
Xi'an Technological University, Xi'an 710021, Shaanxi, China

Dengxin Hua

School of Mechanical and Precision Instrument Engineering,
Xi'an University of Technology, Xi'an 710048, Shaanxi, China

Abstract
In order to address the problem that traditional passive suspension damping parameter cannot be adjusted which makes it difficult to improve vehicle ride comfort and handling stability, the paper proposes use of controllable magneto-rheological dampers in replace of passive dampers to establish semi-active suspension based on magneto-rheological dampers. By designing magneto-rheological damper reverse model based on BP neural network, it solves the problem of reverse request of input current required with expected damping force and damper piston relative displacement, forms closed loop feedback system with the inverse model and the designed fuzzy PID controller and achieves semi-active control of vehicle suspension. The experimental results and data analyses of inputting different road excitation in the system show that the intelligent hybrid control method proposed in this paper can effectively improve the vehicle ride comfort and handling stability and improve suspension system performance. This paper conducts comparative analyses of vehicle semi-active suspension system performance for the cases of different speeds on different roads, which further validate rationality and effectiveness of the method.

Key words: VEHICLE SUSPENSION SYSTEM, SEMI-ACTIVE CONTROL, FUZZY-PID, MAGNETO-RHEOLOGICAL DAMPER, BP NEURAL NETWORK

1. Introduction

As one of assemblies of vehicle, suspension system [1] plays the role of road shock cushion and attenuation of vibration due to uneven pavement. Suspension system performance directly affects vehicle ride comfort and handling stability. Nonetheless, traditional passive suspension has significant limitation in coordination of these two vehicle performance, unable to meet requirement of vehicle [2]. Therefore, researchers carried out researches on non-passive suspension system. While active suspension system overcomes the shortcomings of passive suspension system, due to its high energy consumption and high cost, so far no active suspension with good performance and low cost has not been applied. Semi-active suspension system[3], as a compromise between traditional passive suspension system and active suspension system, can change spring stiffness or shock absorber damping coefficient of suspension system within a certain range based on vehicle state. Due to its performance close to active suspension control, simple structure, low cost, low energy consumption and stable performance, it has received wide attention in the vehicle industry, becoming emerging technology and research focus in vehicle marketing application.

Control technology is the key issue in the study of semi-active suspension. Scholars and researchers have conducted a lot of research work in the control method of vehicle semi-active suspension system. The most representative is the Skyhook damping control strategy [4], but its control is not continuous. Moreover, it requires that damper has a relatively wide frequency band; otherwise it is difficult to improve the suspension performance. In vehicle semi-active suspension, commonly used methods also include optimal control [5], but it only ensures expected performance of ideal mathematical model, ignoring the nonlinear suspension system with many uncertain factors, difficult to meet actual needs. Traditional PID [6] control algorithm is simple and easy to achieve, but has limitations in solving complex and instability problems. In addition to these conventional methods, many scholars began to adopt intelligent control method [7] to study control problem of semi-active suspension, such as fuzzy control and neural network control. They are with good flexibility, strong adaptability, but dependent on expertise with strong subjectivity. Thus, various control methods have advantages and disadvantages, and use of a single control method is difficult to achieve the desired control effect. Therefore, hybrid control strategy that combines a variety of control methods can be adopted to achieve effective control purposes.

In recent years, magneto-rheological damper [8], as intelligent controllable absorber, has been widely used in vehicle semi-active suspension thanks to its fast response, simple structure and low energy consumption [9]. So the paper proposes use of neural network [10] to build inverse model of magneto-rheological damper to obtain continuous control current, thus realizing continuous control of damping force. By combining fuzzy control theory and PID control [11], it forms closed loop feedback to achieve semi-active control of vehicle suspension, thus improving the vibration attenuation performance of vehicle.

2. System modeling

2.1. 1/4 Vehicle semi-active suspension model with 2 degrees of freedom

Classic two degree of freedom 1/4 vehicle semi-active suspension model [12] describes the vehicle vibration in the vertical direction. Its suspension dynamic performance (body vertical acceleration, suspension dynamic deflection and tire dynamic load) reflects vehicle ride comfort and handling stability. Two degree of freedom 1/4 suspension model is shown in Figure 1.

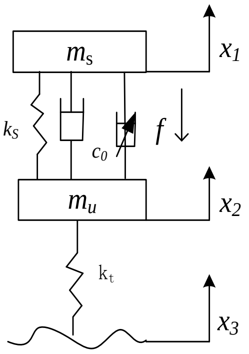


Figure 1. 1/4 vehicle semi-active suspension model with 2 degrees of freedom

Where m_s is the sprung mass, m_u is the unspruing mass, k_s is the rigidity of the suspension spring, k_t is the tyre rigidity, f is the adjustable damping force, c_0 is the passive dampness coefficient of the suspension damper, x_1 is the displacement of the sprung mass, x_2 is the displacement of the unsprung mass, and x_3 is the road disturbance.

According to Newton’s second law of motion, the differential equation of 1/4 vehicle semi-active suspension system with 2 degrees of freedom can be obtained:

$$\begin{cases} m_s\ddot{x}_1 + k_s(x_1 - x_2) + c_0(\dot{x}_1 - \dot{x}_2) - f = 0 \\ m_u\ddot{x}_2 - k_s(x_1 - x_2) - c_0(\dot{x}_1 - \dot{x}_2) + k_t(x_2 - x_3) + f = 0 \end{cases}$$

(1)

To assess control effect of the semi-active suspension, the body acceleration $\ddot{x}_1$, suspension dynamic deflection x_1-x_2 and tyre dynamic load x_2-x_3, which can indicate vehicle ride comfort, handling stability and security, are selected as the system output. Build vehicle semi-active suspension simulation model in MATLAB/Simulink based on the differential equation, as shown in Figure 2.

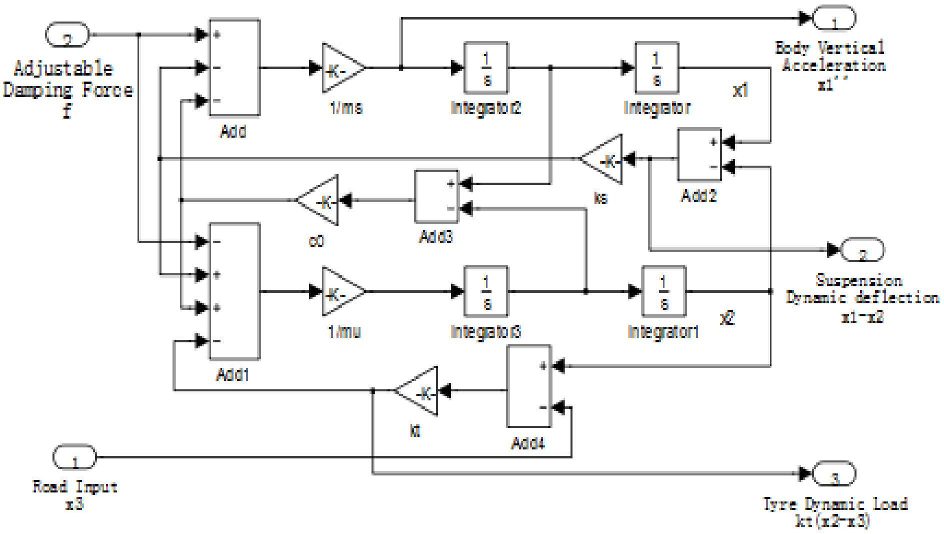


Figure 2. Simulation model of vehicle semi-active suspension

2.2. Magneto-rheological damper model

The biggest difference between semi-active suspension and passive suspension is that damping force generated in semi-active suspension damper can be changed by adjustment of damping coefficient. As a result, damping force of the system can be real-time controlled based on road conditions to suppress vehicle vibration. Magneto-rheological damper has been widely used in the vehicle suspension as suspension system actuator due to its large output, low energy consumption, fast response and easy connection to Microcomputer control. Magneto-rheological damper works by changing mobility of damp channel magneto-rheological fluid to obtain varied damping coefficient. Magneto-rheological features are related to different intensities of magnetic fields obtained by adjusting current in exciting coil. Magneto-rheological damper phenomenon model based on Bouc-Wen hysteresis operator proposed by Spencer [13] has been widely used due to its more accurate description of nonlinear hysteresis and saturation characteristic of magneto-rheological damper, and its strong universality, as shown in Figure 3.

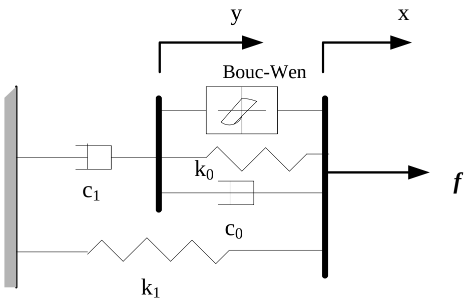


Figure 3. Magneto-rheological damper phenomenon model

From the model, damping force equation can be obtained as:

$$\begin{cases} f = c_1\dot{y} + k_1(x - x_0) \\ \dot{y} = \dfrac{1}{c_0 + c_1}\left[\alpha z + c_0\dot{x} + k_0(x - y)\right] \\ \dot{z} = -\gamma\left|\dot{x} - \dot{y}\right| z \left|z\right|^{n-1} - \beta(\dot{x} - \dot{y})\left|z\right|^{n} + A(\dot{x} - \dot{y}) \end{cases} \qquad (2)$$

Where f is the output damping force of magneto-rheological damper, c_1 is viscous damping at low speed, c_0 is viscous damping at high speed, k_1 is stiffness of accumulator, k_0 is stiffness coefficient at high speed, x is relative displacement of spring (i.e., relative displacement of sprung mass and unsprung mass), x_0 is initial relative displacement, y is internal displacement, z is evolution variable, α is scale factor of Bouc-Wen hysteresis operator, γ, β, A, are correlation coefficients of hysteresis characteristic, n is index coefficient, generally is 2. Parameters c_0, k_0, k_1, x_0,γ, β, A and n are constant values, parameters c_1 and α are functions of input current. Through curve fitting with linear function according to experimental data [7], obtain:

$$\begin{cases} c_1 = c_{1a} + c_{1b} i = 8.168 + 2.725 i \\ \alpha = \alpha_a + \alpha_b i = 0 + 1.723 i \end{cases} \qquad (3)$$

Parameter values obtained by identification are shown in Table 1[14]:

Table 1. Parameter values of magneto-rheological damper phenomenon model

Parameter/unit	value	Parameter/unit	value	Parameter/unit	value
$c_0 / N \cdot s \cdot mm^{-1}$	0.977	$\alpha_b / N \cdot mm^{-1}$	1.723	β / mm^{-2}	0.07
$c_{1a} / N \cdot s \cdot mm^{-1}$	8.168	$k_0 / N \cdot mm^{-1}$	1.072×10^{-2}	A	300
$c_{1b} / N \cdot s \cdot mm^{-1} \cdot A^{-1}$	2.725	$k_1 / N \cdot mm^{-1}$	0.134	γ / mm^{-2}	0.07
$\alpha_a / N \cdot mm^{-1}$	0	x_0 / mm	114.9	n	2

Magneto-rheological damper dynamic model established in Simulink according to equation sets 2, 3 is shown in Figure 4.

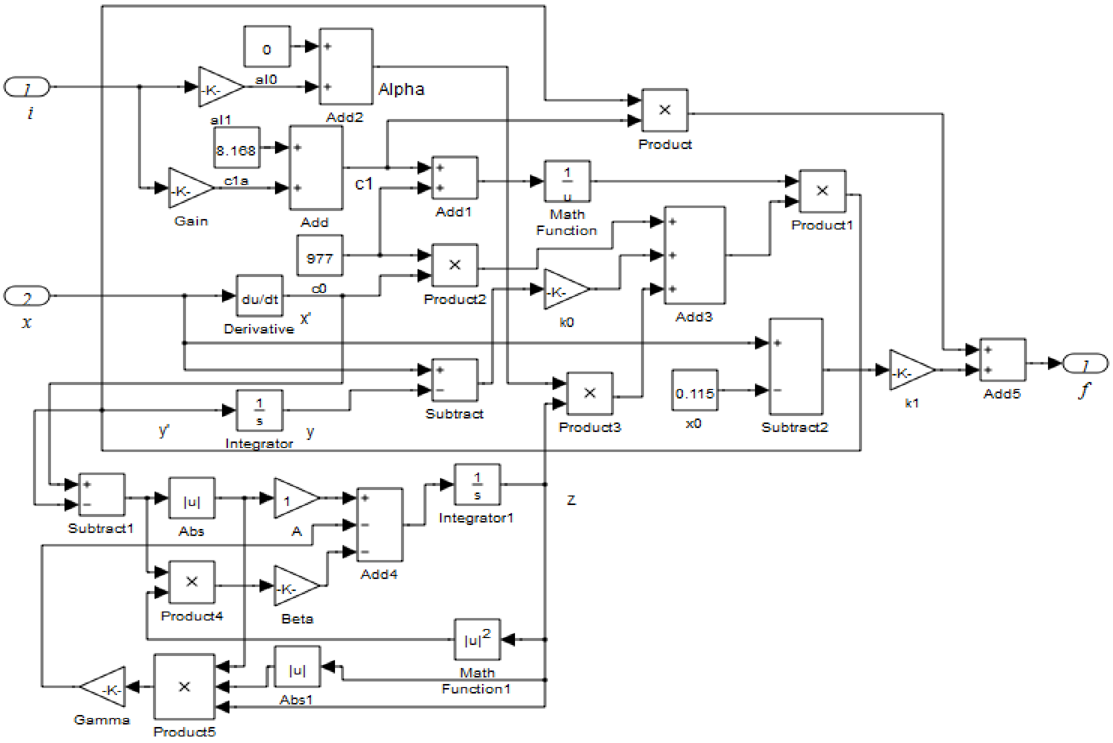
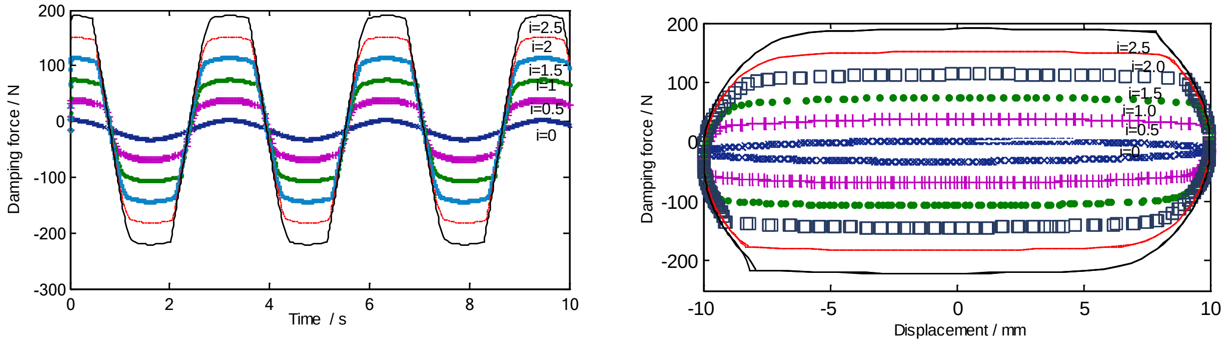
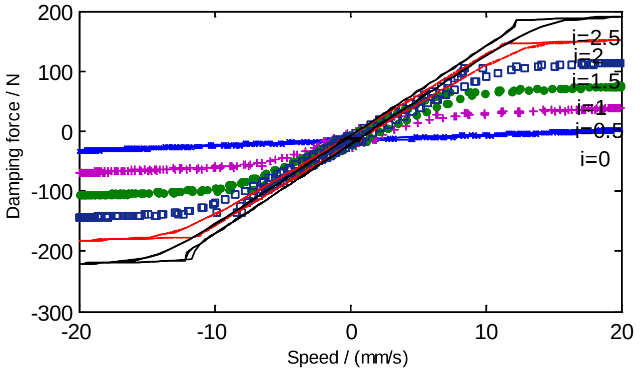


Figure 4. Dynamic simulation model of magneto-rheological damper

Apply sinusoidal displacement excitation with frequency f=2Hz and amplitude A=10mm to magneto-rheological damper phenomenon model, and then collect damping force time domain curve, damping force - displacement curve and damping force - speed curve at different currents, as shown in Figure 5 (a), (b), (c) respectively.



(a) The damping force time domain curve (b) Damping force - displacement curve



(c) Damping force - speed curve

Figure 5. Characteristic curves of magneto-rheological damper change with current

It can be obtained from analysis of Figure 5 that, on the condition that amplitude and frequency of input excitation remain unchanged, when magneto-rheological damper input current increases, its output damping force increases, and hysteresis relation between output damping force and displacement, velocity is very clear, indicating that the model can accurately describe dynamic characteristic of magneto-rheological damper.

2.3. Road input model

Uneven pavement is the main reason for vehicle vibration that affects vehicle ride comfort and handling stability. Therefore, establishment of road excitation input model is a prerequisite for vehicle suspension control study. There are two aspects of continuous vibration and shock effect for pavement input. Continuous vibration refers to continuing unevenness from the pavement, generally applying random road model based on filtering white noise; shock effect refers to vibration caused by bumps or pits on a flat road, with relatively short duration and high intensity. This paper adopts trapezoidal deceleration strip model to study vehicle vibration caused by shock effect.

(1) Random road excitation model

This paper adopts filtering white noise method to generate time profile [15, 16] of road roughness. The time domain model is:

$$\dot{q}(t) = -\alpha v q(t) + \omega(t) \qquad (4)$$

Where $q(t)$ is the road surface random excitation on the wheel, v is the driving speed of vehicles, $\omega(t)$ is the band-limited white noises, and α is a constant coefficient. When the road surface grades are different, α is different. The time domain simulation model of random excitation is shown as the figure 6.

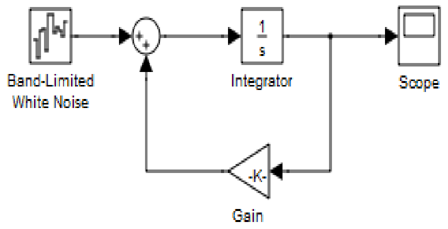


Figure 6. Time domain simulation model of road random excitation

(2) Deceleration strip road excitation model

Deceleration strip is also referred to as decelerating ridge, which is installed in the highway to make pavement slightly arch in order to achieve the purpose of vehicle deceleration. Reducing impact of vehicle when it passes deceleration strip can improve vehicle ride comfort and handling stability [17]. Common pavement bump is with semicircular embossment, trapezoid and other shapes. In this paper, according to the actually measured geometry parameter of a trapezoid deceleration strip, cross section profile approximates isosceles trapezoid [18], as shown in figure 7:

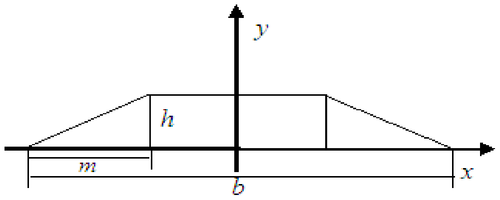


Figure 7. Cross section profile of a trapezoid deceleration strip

Where *h* is the vertical height of deceleration strip, *b* is base width; *m* is parameter of trapezoidal deceleration strip cross section profile. From Figure 7, function expression of trapezoidal cross section profile can be obtained:

$$y=\begin{cases}\frac{h}{m}x+\frac{hb}{2m} & -\frac{b}{2}\le x<-\frac{b}{2}+m\\ h & -\frac{b}{2}+m\le x<\frac{b}{2}-m\\ -\frac{h}{m}x+\frac{hb}{2m} & \frac{b}{2}-m\le x<\frac{b}{2}\end{cases} \qquad (5)$$

3. Control system of vehicle semi-active suspension

The core of semi-active suspension system uses controllable damper as the actuator, with its control performance near that of active suspension [19]. This paper mainly studies semi-active suspension control based on magneto-rheological damper. Its system block diagram is shown in Figure 8. With road excitation x_3 as system input, make suspension system vibrate. Fuzzy PID controller calculates the expected control force *F* based on vertical velocity $\dot{x}$ and acceleration $\ddot{x}$ of sprung mass m_s. With inverse model of magneto-rheological damper based on BP neural network, needed control current *i* can be obtained according to the expected control force *F* and relative displacement x_1-x_2 (damper piston displacement) of suspension system sprung mass m_s and unsprung mass m_u. Finally, magneto-rheological damper outputs damping force *f* close to the expected control force according to current value, and acts on the suspension system, thus realizing semi-active control and reducing vibration response of the system.

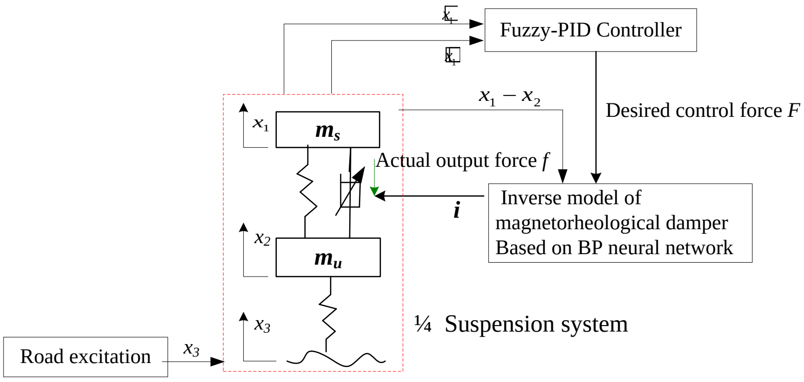


Figure 8. The block diagram of semi-active suspension control system

3.1. Semi-active suspension fuzzy PID control

There are many control methods applied to suspension system, but with both advantages and disadvantages. To combine two or more control methods for hybrid control of suspension system can achieve better results. This paper combines traditional PID control and fuzzy logic to control vehicle suspension system [20], which has both characteristics of PID control of simple operation, stability and reliability and fuzzy controller advantages of simple structure and good adaptability.

In traveling process of vehicle, what is usually most concerned about is body acceleration which impacts ride comfort, so body acceleration is taken as the main control object with suspension dynamic deflection and tire dynamic load as constraints to achieve fuzzy PID control of semi-active suspension system [21]. Take difference *e* between body speed in the vertical direction and reference value (set to 0) and acceleration change *ec* as input variable of fuzzy controller, and three parameters of PID controller, K_p、K_i、K_d, as fuzzy controller output. Fuzzy PID controller output is expected damping force *F* of semi-active suspension system. Fuzzy PID control principle block diagram of the system is shown in Figure 9[22].

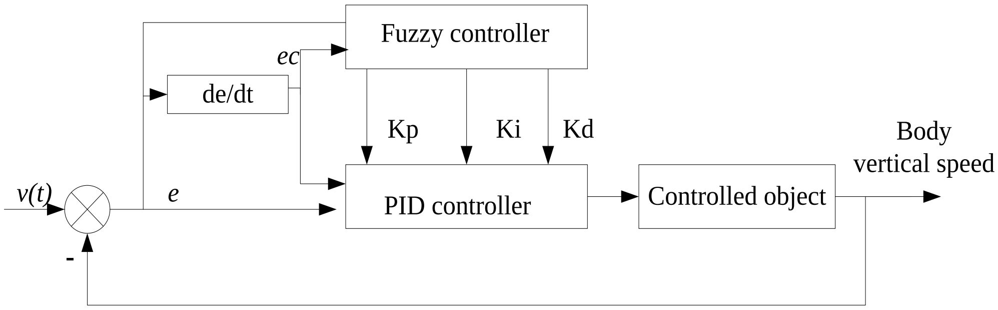


Figure 9. Fuzzy PID control theory

The Value range of input error *e* and fuzzy domain *E* are determined by range of the vertical speed of the vehicle. In practice, the vertical speed of the vehicle varies within [-0.15, 0.15], so the basic domain of the input error *e* can be set as [-0.15, 0.15]. The fuzzy domain *E* is set as [-3, 3], then the quantification factor of the difference *e* [23] is k_e=3/0.15=20. Under the same fuzzy domain, the body's vertical acceleration varies within [-3, 3], so the quantification factor of difference change rate *ec* is k_{ec}=3/3=1.

In design of the fuzzy controller, the input variant *e*, *ec* and output variant K_p, K_i and K_d are selected from 7 fuzzy subsets: negative big (NB), negative middle (NM), negative small (NS), zero (ZO), positive small (PS), positive middle (PM) and positive big (PB). The corresponding fuzzy domain of the input variants and output variants are [-3, -2, -1, 0, 1, 2, 3]. The fuzzy control rules of K_p are shown from table 2. The fuzzy control rule of K_i and K_d is similar to that of K_p。

Table 2. Control rules of K_p

K_p		*e*						
		NB	NM	NS	ZO	PS	PM	PB
ec	NB	PB	PB	PM	PM	PS	PS	ZO
	NM	PB	PB	PM	PM	PS	ZO	ZO
	NS	PM	PM	PM	PS	ZO	NS	NM
	ZO	PS	PS	PS	ZO	NS	NM	NM
	PS	PS	PS	ZO	NS	NS	NM	NM
	PM	ZO	ZO	NS	NM	NM	NM	NB
	PB	ZO	NS	NS	NM	NM	NB	NB

Use Matlab built in fuzzy logic toolbox to edit fuzzy control rules. Select Mamdani type as controller type, input fuzzy control rules with if-then form to generate fuzzy inference system FIS file. Link FIS file with fuzzy PID simulation model established in Matlab/Simulink software, and then achieve fuzzy PID control of vehicle semi-active suspension system. Fuzzy PID simulation model of vehicle semi-active suspension system is shown in Figure 10.

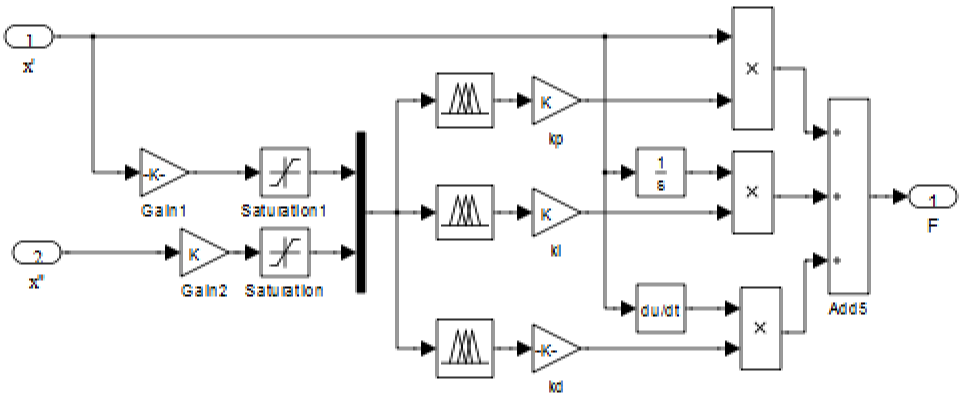


Figure 10. Fuzzy PID simulation model of vehicle semi-active suspension system

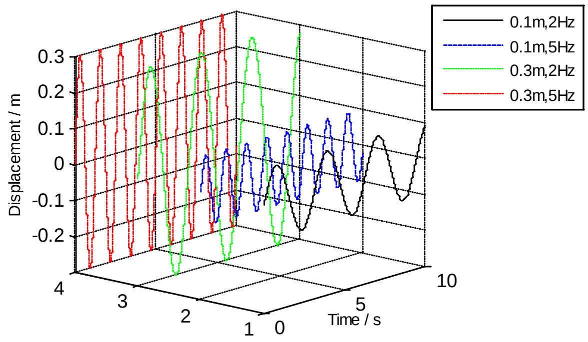
3.2. Magneto-rheological damper reverse model based on BP neural network

Magneto-rheological damper, an intelligent absorber with adjustable damping force, has been widely used in a variety of vibration attenuation systems. Output damping force of magneto-rheological damper is determined by relative displacement of piston and control current of damper. When magneto-rheological damper is used in semi-active control of suspension system [24], control algorithm will calculate the control force to mitigate the vibration in accordance with vibration response generated in the system. If damper is to produce the expected damping force, it is necessary to solve the inverse problem of reverse request of input current based on expected damping force and relative displacement of piston, which requires establishment of magneto-rheological damper dynamics inverse model which is an indispensible part to achieve semi-active control of vehicle suspension.

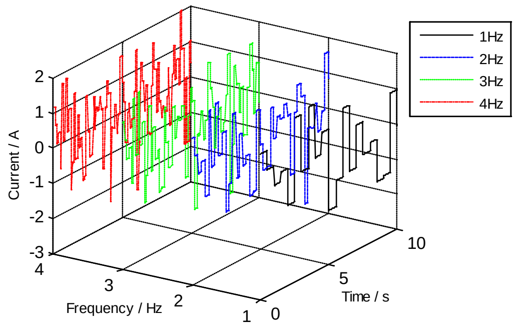
This paper takes advantage of strong learning ability and approximation to any nonlinear function of BP neural network [25] to build magneto-rheological damper dynamics inverse model [26], to address the inverse problem of reverse request of needed control current based on expected damping force and relative displacement of piston. Finally, form a closed loop feedback with the inverse model and fuzzy PID controller, thus achieving semi-active control of magneto-rheological semi-active suspension.

According to Kolrnogorov [27] theorem, any continuous function in a closed interval can be approximated by a single hidden layer BP network. Therefore, select a three-tier neural network to build magneto-rheological damper inverse model. According to dynamic characteristic of magneto-rheological damper, input layer has eight nodes which are input displacement, damping force and current of the first two moments, as well as input displacement and damping force at the current moment, while output layer has a node, control current at the current moment.

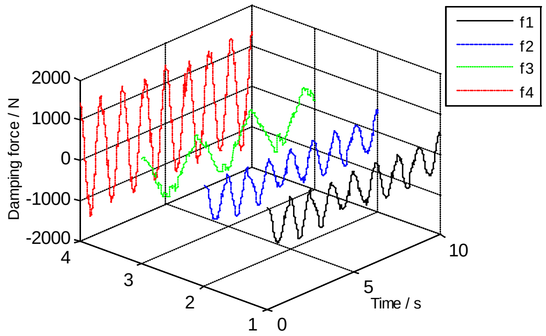
In order to make the training sample data cover the entire operating range of damper, select training and validation data as follows: displacement input is sinusoidal excitation with amplitude 0.1m, 0.3m, frequency 2Hz, 5Hz; input current adopts Gaussian white noise with frequency range in 1-4Hz, thus ensuring effectiveness of trained magneto-rheological damper neural network inverse model[28]. Input and output data are generated by the established model, which sampling frequency is 500 Hz and sampling time is 10s. Generate 5000 sets of data according to the model, with 1 to 3000th set of data as training sample data of network and the remaining 2000 sets for testing the trained network. Figure 11 is training sample data, wherein (a) is input displacement, (b) is input current, and (c) is output damping force.



(a) Displacement input curves



(b) Current input curves



(c) Damping force output curves

Figure 11. Samples training

The initial 3000 sets of data used to train sample network achieve optimal BP network model after 174 times of training when the number of hidden nodes is 18. The mean square error (MSE) is 0.0344.

After the training is completed, take the remaining 2000 sets of data as input of the trained reverse neural network model, conduct test and verification of the reverse model without changing connection weight coefficient, and then compare the predictive values of the model with the actual output values. The results are shown in Figure 12, it can be seen that the predictive values approache to the actual values, and can well track target value.

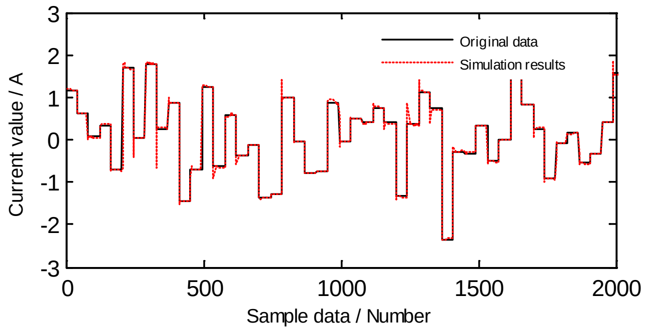


Figure 12. Compare of the predictive current and the actual current

To verify the generalization of inverse neural network model, inputting sinusoidal displacement excitation with amplitude at 20 mm, frequency at 3Hz and current that linearly varies with time tests reverse neural network model. Simulation results of predictive current and target current are shown in Figure 13. The relative error curve is shown in Figure 14.

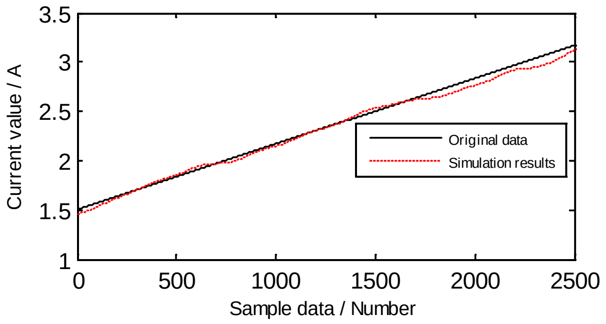


Figure 13. Contrast curve of predictive current and target current

As can be seen from Figure 13, the trained reverse neural network model exhibits good adaptability to new input. From Figure 14, it can be seen that error between the predictive current and the target current is in permissible range, indicating that the model has strong generalization ability. Thus, applying the reverse neural network model of magneto-rheological damper to control of semi-active suspension system, under the circumstance that the input vibration response and expected control force are known, can predict the needed current of damper to achieve continuous adjustment of damping force.

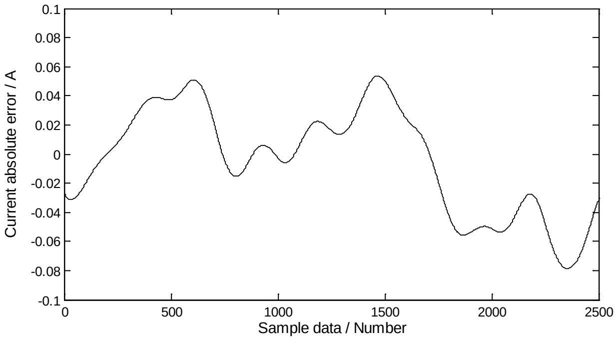


Figure 14. The error curve of predictive current and target current

4. Simulation result and analysis

Based on the control principle of vehicle semi-active suspension system, overall fuzzy PID control simulation model of vehicle magneto-rheological semi-active suspension system can be obtained, as shown in Figure 15, where Neural Network is magneto-rheological damper inverse model based on BP neural network. Suspension parameters in the simulation are shown in Table 3.

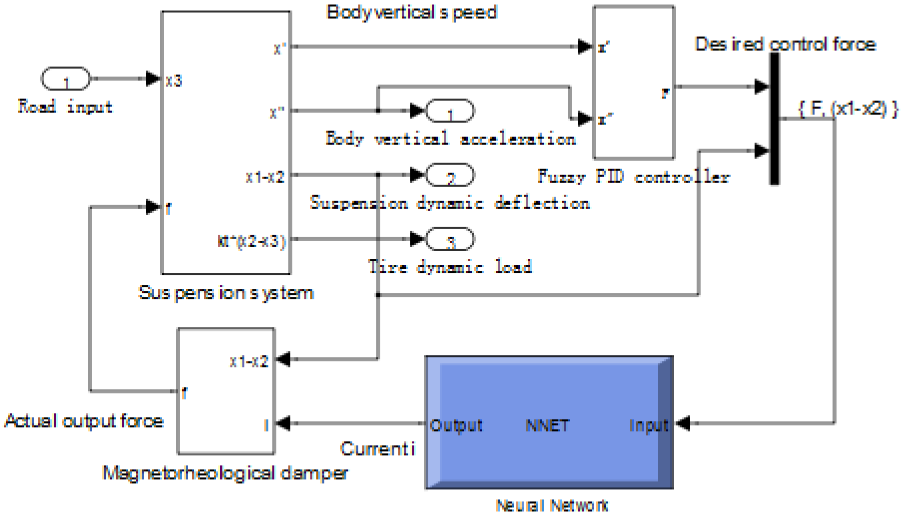


Figure 15. Overall simulation diagram of semi-active suspension

Table 3. Vehicle suspension parameters

Parameter/unit	m_s/kg	m_u/kg	k_s/(N·m^{-1})	k_t/(N·m^{-1})	c_0/(N·s·m^{-1})
value	487.685	49	45480	604690	2546.5

4.1. Simulation analysis of random white noise input

When vehicle runs on Grade B road at constant speed of 50km/h, road random signal input curve, simulation results of body vertical acceleration, suspension dynamic deflection, tire dynamic load of passive suspension, PID control semi-active suspension and fuzzy PID control semi-active suspension are shown in Figure 16. The table 4 shows the RMS of performance index of those suspensions.

The simulation results in Figure 16 indicate that performance of fuzzy PID control and PID control semi-active suspension based on magneto-rheological damper have improved significantly compared to that of passive suspension. Comparison of RMS of various performance indexes in Table 4 reveals that, when vehicle runs on Grade B road at constant speed of 50 km/h, RMS of body acceleration, suspension dynamic deflection and tire dynamic load of traditional PID control semi-active suspension decrease by 20.22%, 10.84%, 18.66% respectively compared to those of passive suspension, while those of fuzzy PID control suspension decrease by 27.94%, 15.16%, 21.71%.

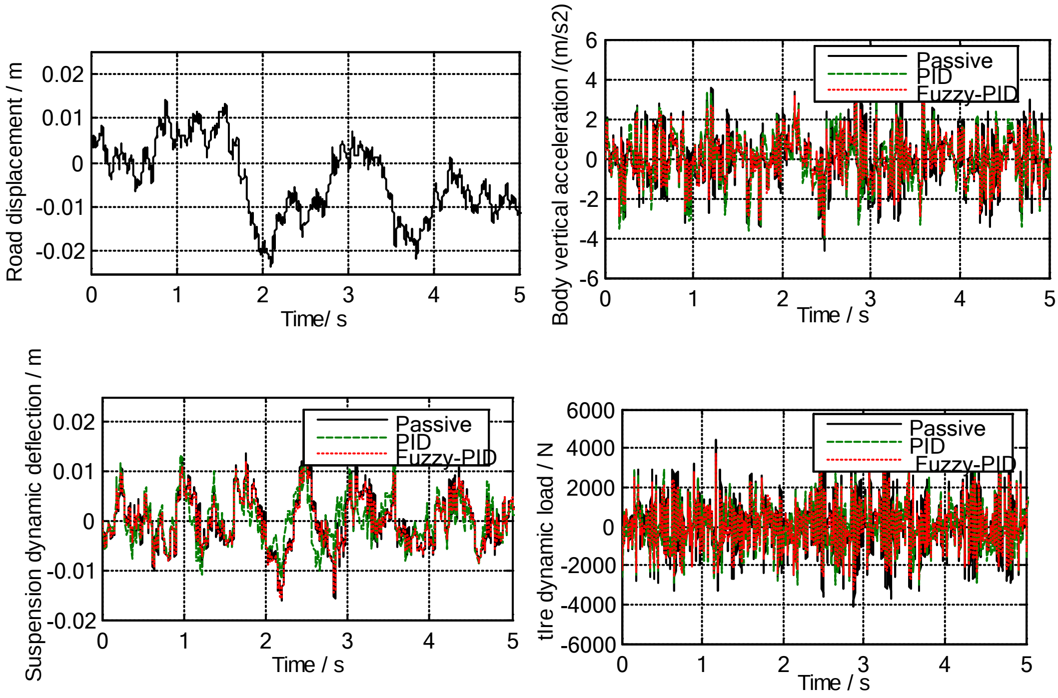


Figure 16. Simulation curves at random road input on Grade B road at speed of 50 km/h

Table 4. The RMS of suspension performance index on Grade B road at speed of 50 km/h

The RMS of performance indicators	Passive suspension	PID controlled suspension	Fuzzy-PID controlled suspension	performance improvement/%	
				PID	Fuzzy PID
body's acceleration/(m/s^2)	0.995	0.794	0.717	20.22	27.94
suspension dynamic deflection/mm	3.957	3.528	3.357	10.84	15.16
tyre's dynamic load/N	1025	834	803	18.66	21.71

The results show that vehicle ride comfort and handling stability of fuzzy PID control semi-active suspension have been greatly improved, validating effectiveness and feasibility of fuzzy PID control method based on magneto-rheological damper designed in this paper.

4.2. Simulation analysis of vehicle passing through deceleration strip

When vehicle runs through deceleration strip 3cm in height at a speed of 10 km/h, road shock input signal curve, simulation results of body vertical acceleration, suspension dynamic deflection and tire dynamic load of passive suspension, PID control semi-active suspension and fuzzy PID control semi-active suspension are shown in Figure 17. The table 5 shows the RMS of suspension performance indexes.

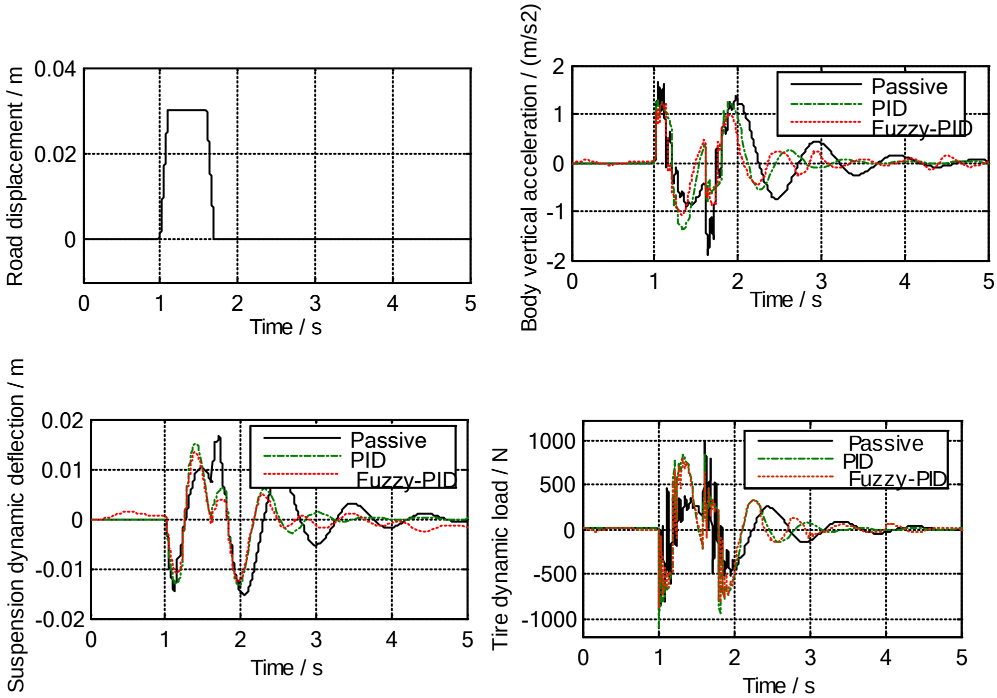


Figure 17. Simulation curves under deceleration strip road excitation

Table 5. The RMS of suspension performance index under deceleration strip road excitation

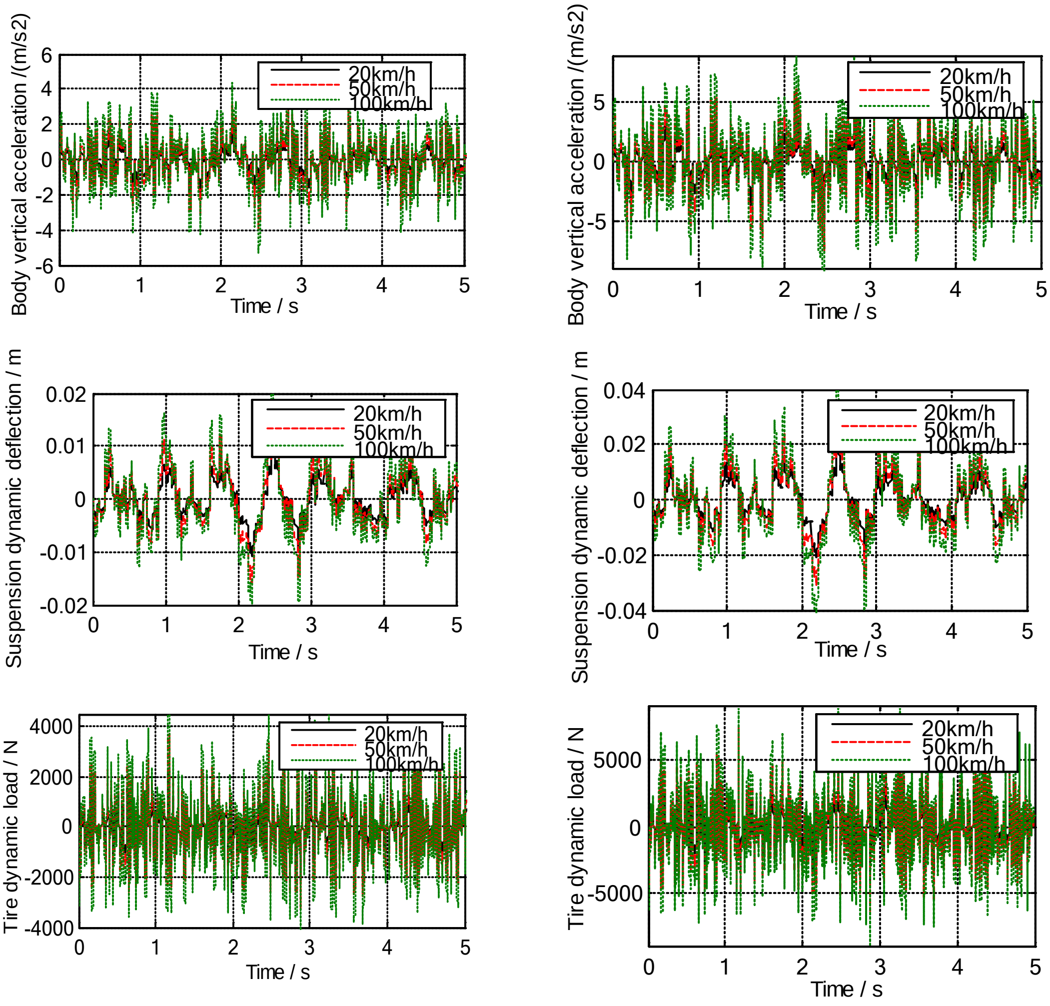
The maximum of performance indicators	Passive suspension	PID controlled suspension	Fuzzy-PID controlled suspension	performance improvement/%	
				PID	Fuzzy PID
body’s acceleration/(m/s^2)	1.67	1.405	1.3405	15.87	19.73
suspension dynamic deflection/mm	16.501	14.998	13.498	9.09	18.18
tyre’s dynamic load/N	990	853	819	13.84	17.27

Simulation results of vehicle running through trapezoid deceleration strip 3cm in height at a speed of 10 km/h and comparison of maximum values of various performance indexes reveal that, body vertical acceleration, suspension dynamic deflection and tire dynamic load of magneto-rheological semi-active suspension system based on PID control respectively improve 15.87%, 9.09% and 13.84% compared to those of passive suspension system; and various performance indexes of magneto-rheological semi-active suspension system based on fuzzy PID control improve 19.73%, 18.18% and 1.27% respectively compared to those of passive suspension system. Simulation of vehicle passing through deceleration strip can further validate rationality and effectiveness of semi-active suspension system fuzzy PID control method designed in this paper based on magneto-rheological damper.

4.3. Simulation analysis of vehicle at different speeds on different roads

When the road grade is B and speeds are respectively 20km/h, 50km/h, 100km/h, simulation results of fuzzy PID control semi-active suspension system based on magneto-rheological damper are shown in Figure18(a). Simulation results on Grade C road are shown in Figure 18(b).

Table 6 shows RMS of various performance indexes of simulation results when the road input excitation is a random white noise signal, vehicle speed are 20 km/h, 50 km/h and 100 km/h respectively, and road grades are B, C.



(a) Grade B road

(b) Grade C road

Figure 18. Simulation curves at different speeds on different roads

Table 6. The RMS of suspension performance index at different speed on different roads

the RMS of Performance indicators	20km/h		50km/h		100kn/h	
	Grade B road	Grade C road	Grade B road	Grade C road	Grade B road	Grade C road
body's acceleration/(m/s^2)	0.518	0.527	0.717	0.729	2.096	2.124
suspension dynamic deflection/m	2.453	2.52	3.357	3.511	8.944	9.179
tyre's dynamic load/N	510	545	803	832	2053	2231

It can be known from Figure 18 and Table 6 that, at the same road grade, when traveling speed accelerates, RMS of the three performance evaluation indexes of suspension system will increase significantly, meaning that the greater vehicle speed, the lower suspension performance and worse vehicle ride comfort, handling stability and security. Therefore, drivers shall control the vehicle speed while driving vehicles in order to drive effectively and safely.

The simulation results and comparisons of RMS of various performance indexes reveal that, when vehicle runs on roads of different grades at the same speed, RMS of body vertical acceleration, suspension dynamic deflection and tire dynamic load of suspension system vary little indicating that, change in road grade has little effect on ride comfort and handling stability of vehicle based on magneto-rheological semi-active suspension, showing that good suspension will adjust according to road condition changes.

5. Conclusions

In order to overcome the non-adjustable damping parameter of passive damper, the paper use magneto-rheological damper in replace of traditional passive damper. The established magneto-rheological damper inverse model outputs continuous current to control continuous damping force generated by damper and thus achieves adjustable damping. By forming a closed loop feedback of magneto-rheological damper inverse model based on neural network and fuzzy PID controller, it achieves semi-active control of vehicle suspension to improve vehicle ride comfort and handling stability.

It can be obtained through simulation verification and analysis results that: compared to passive suspension system and PID control semi-active suspension system, vehicle magneto-rheological semi-active suspension system based on fuzzy PID control can effectively reduce body vertical acceleration and tire dynamic load, improve vehicle ride comfort and handling stability. When the road input grades are the same and traveling speeds are different, the greater vehicle speed, the greater RMS of body vertical acceleration, suspension dynamic deflection and tire dynamic load of suspension system, i.e. vehicle ride comfort and handling stability will correspondingly deteriorate; when the driving speeds are the same and road input grades are different, change in road grade has little effect on vehicle ride comfort and handling stability and security.

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