Research on Preview-Fuzzy Control Strategy Based on MR Damper in Railway Vehicle

Ma Xinna\textsuperscript{1}, Shi Wenrui\textsuperscript{1}, Liu Jingwei\textsuperscript{1}

\textsuperscript{1}School of Information Science and Technology, Shijiazhuang Tiedao University, Shijiazhuang 050043, Hebei, China
\textsuperscript{*}Corresponding author’s e-mail: maxinnamxn@163.com

Abstract: With the increasing speed, the vibration control of high-speed railway vehicle suspension system becomes more and more important. In view of the nonlinearity of high-speed vehicle and the time-delay problem of control system, a new intelligent material magnetorheological damper (MRD) is introduced. On the basis of analyzing the dynamic characteristics of MR damper, a vertical dynamic model of high-speed railway vehicle system based on MR damper is established. In order to suppress the vertical vibration of suspension system, a preview-fuzzy control strategy based on MR damper is proposed. In order to verify the availability of the control strategy, a lot of simulations are carried out. The results show that the preview-fuzzy control strategy based on MR damper can effectively reduce the vibration amplitude of the suspension system and solve the problem of time delay to a certain extent.

1. Introduction

With the development of global economy, the interconnection between economies is deepening. Railway as an economic and environmental transport mode has been sustained development. With the increase of running speed, the vibration of suspension system becomes more serious. Excessive vibration will not only affect the comfort of driving, but also cause chain reaction, accident and even disastrous consequences. Therefore, it is necessary to study the vibration control of high-speed railway vehicle.

Over the years, there have been many studies and applications on passive control, active control and semi-active control strategies. Many achievements have been made in the theoretical research of on-off control, skyhook control and intelligent control strategies such as wavelet, self-learning and fuzzy control strategies [1-3]. Among them, fuzzy control strategy is widely used because of its simple and effective. It can centralize the existing experience into the control algorithm, which can be adjusted online in time and avoid falling into local optimization. Moreover, it does not need a lot of statistical data. Therefore, the fuzzy control strategy is a good choice for the strong non-linear characteristics of high-speed railway vehicle [4-6].

Due to the limitation of signal transmission, calculation and response in control system, time delay becomes an unavoidable problem. Time delay will not only increase the dimension of the system (theoretically, the system will become infinite dimension), but also significantly change the characteristics of the control system. As one of the new intelligent materials, magnetorheological fluid has the characteristics of fast response and good reversibility. Compared with other vibration control devices, MR damper has continuous variable control and regulation performance, and can implement...
precise real-time control. It has been applied in many fields, such as artificial knee damper, clutch for mechanical transmission, bridge cable damper and so on [7-9].

Considering the operation characteristics of high-speed railway and the time-delay problem in vibration control system, a preview-fuzzy control strategy based on MR damper is proposed. After analyzing the dynamic characteristics of MR damper, the dynamic model of high-speed railway vehicle with preview-fuzzy control strategy based on MR damper is established. In order to verify the effectiveness of the preview-fuzzy control strategy in suspension system, simulation analysis is carried out under the software of Matlab and Simulink. The vibration control effects under different control strategies are discussed in detail.

2. Analyses of Dynamic Characteristics of MR Damper

Magnetorheological fluids (MRF) are suspended liquids consisting of three parts: ferromagnetic particles, non-magnetic carrier liquid and additives. The damping force of MR damper is affected by magnetic intensity, displacement amplitude and excitation frequency. In order to accurately describe the dynamic properties of MR dampers, many models have been proposed. Among them, the Bouc-Wen model has smooth transition curve, which is easy to carry out numerical calculation and has strong versatility. In this paper, the Bouc-Wen cubic modified model is adopted. In this model, the damping force of MR damper is expressed as the sum of viscous force and hysteretic damping force. The principle of dynamic model [10] is shown in Figure 1.

The expression of damping force generated by MR damper can be expressed as:

\[ F = c_0 \dot{x} + \alpha z \]  

In Formula (1), the parameter \( Z \) is the hysteretic displacement.

\[ \dot{z} = -\gamma \exp(\dot{x})z^3 - \beta \dot{z}^3 + A\dot{x} \]  

The parameter \( A \) is the hysteresis displacement coefficient, and the parameters \( A \) and \( c_0 \) are functions of the excitation electrical currents on the damper.

\[ A(I) = 11915 \times 0.5475 I \]  

\[ c_0(I) = 269.5 \exp(I/0.83) \]  

The parameters \( c_0, \gamma \) and \( \beta \) are invariant constants for the fixed MR fluid and MR damper. Through multiple experiments, they can take values of 600, 500 and 1000 respectively. Therefore, the hysteresis curve of velocity-damping force is obtained by simulation. The relationship among velocity, electric current and damping force is obtained as shown in Figure 2.
Figure 2. The relationship among velocity, electric current and damping force.

From Figure 2, it can be seen that the damping force increases with the increase of the vibration speed. The relationship between them is approximately linear in the positive and negative velocity section. There is a certain hysteresis between velocity and damping force, which must be considered in the application of MR dampers. We can see that there is smooth transition curve among velocity, current and damping force. The damping force increases with the increase of current, but it is not linear. With the further increase of current, the growth rate of damping force decreases and tends to be saturated. The nonlinear characteristics of MR dampers bring great difficulties to the design and analysis of control strategies.

3. Dynamic Model of High Speed Railway Vehicle with MR dampers

With the whole vehicle as object of study, we focus on the vertical vibration. Considering the vertical, side rolling and nodding motions of the body and bogies, rolling and nodding motions, and the vertical motion of the wheel sets, a 17-DOF vertical dynamic model of the whole railway vehicle based on MR dampers is put forward, as shown in Figure 3.

Figure 3. Vertical dynamic model of railway vehicle based on MR dampers.

For the vehicle vertical suspension system, assuming that the body and bogie are rigid, they are connected with the secondary suspension system. The wheel sets are connected to the bogie with primary suspension system. The excitation received by wheel sets comes from track irregularity. According to Newton’s law, the motion equation of each component is obtained, and the differential equation of the vertical dynamic model of the 17-DOF railway vehicle is established as follows.

**Wheel sets’ vertical motion:**

\[
M_w \ddot{Z}_{w1} + 2p_1(t) - M_w g = F_{sh}(t) \tag{5}
\]

\[
M_w \ddot{Z}_{w2} + 2p_2(t) - M_w g = F_{sh}(t) \tag{6}
\]

\[
M_w \ddot{Z}_{w3} + 2p_3(t) - M_w g = F_{sh}(t) \tag{7}
\]

\[
M_w \ddot{Z}_{w4} + 2p_4(t) - M_w g = F_{sh}(t) \tag{8}
\]

**Bogies’ vertical motion:**

\[
M_b \ddot{Z}_b + (C_l + 2C_n) \dot{Z}_b + (K_l + 2K_n)Z_b - C_l \dot{Z}_b - K_l \dot{Z}_b - C_l \dot{Z}_b + Z_b - K_l (Z_b + Z_a) - C_l \dot{\beta} - K_l \dot{\beta} - F_l = M_b g \tag{9}
\]

\[
M_b \ddot{Z}_a + (C_l + 2C_n) \dot{Z}_a + (K_l + 2K_n)Z_a - C_l \dot{Z}_a - K_l \dot{Z}_a - C_l \dot{Z}_a + Z_a - K_l (Z_a + Z_b) - C_l \dot{\beta} - K_l \dot{\beta} - F_l = M_b g \tag{10}
\]
Bogies’ nodding motion:
\[
\begin{align*}
I_1\dot{\beta}_1 + 2C_1J_1^{\frac{1}{2}}\dot{\beta}_1 + 2K_1J_1^{\frac{1}{2}}\beta_1 - C_1J_1\dot{Z}_1 - C_1J_1\dot{Z}_s - K_1J_1Z_1 + K_1J_1Z_s &= 0 \\
I_2\dot{\beta}_2 + 2C_2J_2^{\frac{1}{2}}\dot{\beta}_2 + 2K_2J_2^{\frac{1}{2}}\beta_2 - C_2J_2\dot{Z}_2 - C_2J_2\dot{Z}_s - K_2J_2Z_2 + K_2J_2Z_s &= 0
\end{align*}
\]  
(11)  

Bogies’ side rolling motion:
\[
\begin{align*}
J_1\dot{\phi}_1 + K_1\phi_1 - (Z_{es} - Z_s) / l1 + C_1\phi_1 - (\dot{Z}_s - \dot{Z}_s) / l1 + K_1\phi_1 - \phi_1 + C_1\phi_1 - \phi_1(\phi_1 - \phi_1) \\
+ K_1\dot{Z}_1 - \phi_1J_1 - Z_s + \phi_1J_1 - Z_s + \phi_1J_1 - \phi_1J_1 = 0 \\
J_2\dot{\phi}_2 + K_2\phi_2 - (Z_{es} - Z_s) / l2 + C_2\phi_2 - (\dot{Z}_s - \dot{Z}_s) / l2 + K_2\phi_2 - \phi_2 + C_2\phi_2 - \phi_2(\phi_2 - \phi_2) \\
+ K_2\dot{Z}_2 - \phi_2J_2 - Z_s + \phi_2J_2 - Z_s + \phi_2J_2 - \phi_2J_2 = 0
\end{align*}
\]  
(13)  

Body’s vertical motion:
\[
M_s\ddot{Z}_s + 2C_s\dot{Z}_s + 2K_sZ_s = 0
\]  
(15)  

Body’s nodding motion:
\[
I_1\dot{\beta}_1 + 2C_1J_1^{\frac{1}{2}}\dot{\beta}_1 + 2K_1J_1^{\frac{1}{2}}\beta_1 - C_1J_1\dot{Z}_1 - C_1J_1\dot{Z}_s - K_1J_1Z_1 + F_1 = 0
\]  
(16)  

Body’s side rolling motion:
\[
\begin{align*}
J_1\dot{\phi}_1 + K_1\phi_1 - (Z_{es} - Z_s) / l1 + C_1\phi_1 - (\dot{Z}_s - \dot{Z}_s) / l1 + K_1\phi_1 - \phi_1 + C_1\phi_1 - \phi_1(\phi_1 - \phi_1) \\
+ K_1\dot{Z}_1 - \phi_1J_1 - Z_s + \phi_1J_1 - Z_s + \phi_1J_1 - \phi_1J_1 = 0 \\
J_2\dot{\phi}_2 + K_2\phi_2 - (Z_{es} - Z_s) / l2 + C_2\phi_2 - (\dot{Z}_s - \dot{Z}_s) / l2 + K_2\phi_2 - \phi_2 + C_2\phi_2 - \phi_2(\phi_2 - \phi_2) \\
+ K_2\dot{Z}_2 - \phi_2J_2 - Z_s + \phi_2J_2 - Z_s + \phi_2J_2 - \phi_2J_2 = 0
\end{align*}
\]  
(17)  

In the above equations, \(M_{wi}\), \(M_{tj}\) and \(M_c\) are the mass of wheel sets, bogies and bodies (\(i=1..4; j=1...2; \) the same below). \(Z_{wi}\), \(Z_{tj}\) and \(Z_c\) are the vertical displacement of wheel sets, bogies and bodies. The \(\beta_t\) and \(\beta_c\) are the nodding displacement of bogies and bodies. The \(\phi_t\) and \(\phi_c\) are the side rolling displacement of bogies and bodies. \(F_{bi}(t)\) and \(p_i(t)\) are the excitation force functions of each wheel set and the vertical force of the wheel and rail respectively. \(F_1\) and \(F_2\) are the damping forces provided by MR dampers respectively. \(L_C\) and \(l_t\) are respectively the half of the length between bogie centers and the half of bogie fixed axles distance. \(C_p, K_p, C_sp\) and \(K_sp\) are primary suspension vertical damping, vertical stiffness, rolling angle damping and rolling angle stiffness, respectively. \(C_t, K_t, C_st\) and \(K_st\) are vertical damping, vertical stiffness, rolling angle damping and rolling angle stiffness of secondary suspension respectively. \(I_t\) and \(J_t\) are the nodding inertia and rolling inertia of bogies respectively. \(I_c\) and \(J_c\) are the nodding inertia and rolling inertia of the body respectively. \(H_2\) is the distance from the body to the center of the frame, and \(H_1\) is the distance from the center of the frame to the center of the wheel sets.

4. Preview-fuzzy control strategy

Preview control was first proposed by Bender [11]. The main external excitation that affects the vibration of high-speed railway vehicle is the irregularity of tracks. There are two ways to obtain preview information. One is installing a special preview sensor in front of the vehicle to measure the state of the track ahead. Another is assuming that the track irregularity on the rear wheel of the vehicle is exactly the same as that on the front wheel (with only time delay) to use the track irregularity received by the front wheel as the preview of the rear wheel in the controller system [12-14]. The excitation between wheel sets of high-speed railway vehicles is interrelated, not independent. The excitation to each subsequent wheel sets is a simple time delay of the input of the first wheel sets. The irregularity excitation of wheel set can be predicted according to the track irregularity obtained by preview, which can be used to improve the effect of vibration control of vehicle. The track irregularity spectrum can be measured by the track detection vehicle in advance, so it is feasible to take the track spectrum predictive input into account in the design of vibration control strategy.

Based on preview control and fuzzy control theory [15], a preview-fuzzy vibration control system based on MR damper is established for the vertical vibration control of high-speed railway vehicle. Considering that the control target is the vertical acceleration of the body, the input of the fuzzy controller is the vertical acceleration and preview parameters of the body, and the output is the required current of the MR damper.
The irregularity excitation of fixed track is obtained by road detection vehicle, which is used as preview data of preview control. In order to simplify the input of fuzzy control, the track irregularity excitation obtained is parameterized. Considering the preview excitation and vibration of vehicle, the parameter $R$ is introduced to express in the following formula:

$$ R = f(x_i, x_o) = \begin{cases} 
R_1 & x_i \geq 0 \quad \text{and} \quad x_o \geq 0 \\
R_2 & x_i < 0 \quad \text{and} \quad x_o \leq 0 \\
R_3 & x_i / x_o = -1 \quad \text{and} \quad x_i + x_o = 0 \\
R_4 & x_i \geq 0 \quad \text{and} \quad x_i + x_o > 0 \\
R_5 & x_i \geq 0 \quad \text{and} \quad x_i + x_o < 0 \\
R_6 & x_i < 0 \quad \text{and} \quad x_i + x_o \geq 0 \quad \text{and} \quad x_i + x_o < 0 \\
R_7 & x_i < 0 \quad \text{and} \quad x_i + x_o \geq 0 \quad \text{and} \quad x_i + x_o < 0 
\end{cases} $$  

(18)

Among them, $x_o$ expresses the track irregularity excitation in front of the high-speed railway vehicle which can be taken through preview method. $x_1$ represents the current vibration state of the high-speed railway vehicle suspension system. The parameter $R$ and the vertical acceleration $A$ of body are selected as the input variables of the fuzzy controller. The output variable $I$ is the input current of the MR damper. The input variable parameters and vertical acceleration are discretized into seven grades, and the output variable is discretized into nine grades, as shown in the following formulas:

$$ R = \{R_1, R_2, R_3, R_4, R_5, R_6, R_7\} $$  

(19)

$$ A = \{\text{NM}, \text{NB}, \text{NS}, \text{Z}, \text{S}, \text{B}, \text{M}\} $$  

(20)

$$ I = \{\text{NB}_4, \text{NB}_3, \text{NB}_2, \text{NB}_1, \text{Z}, \text{B}_1, \text{B}_2, \text{B}_3, \text{B}_4\} $$  

(21)

According to the fuzzy membership function, the membership degrees are obtained which form the subset of fuzzy variables. The membership functions of both input and output variables are Gaussian functions. The membership functions of output variable are shown in Figure 4.

![Figure 4. Membership function of electric current.](image)

The standard of establishing fuzzy rules is "the fastest acceleration of vehicle body vibration". As a matter of experience, the fuzzy control rule table is summarized and shown in Table 1.

| $R$ | $I$ | $A$ |
|-----|-----|-----|
| $R_1$ | $Z$ | $\text{NB}_4$, $\text{NB}_3$, $\text{NB}_2$, $\text{NB}_1$, $\text{Z}$, $\text{B}_1$, $\text{B}_2$, $\text{B}_3$, $\text{B}_4$ |
| $R_2$ | $\text{B}_4$, $\text{B}_3$ | $\text{NB}_4$, $\text{NB}_3$, $\text{NB}_2$, $\text{NB}_1$, $\text{Z}$, $\text{B}_1$, $\text{B}_2$, $\text{B}_3$, $\text{B}_4$ |
| $R_3$ | $\text{B}_1$, $\text{B}_2$ | $\text{NB}_4$, $\text{NB}_3$, $\text{NB}_2$, $\text{NB}_1$, $\text{Z}$, $\text{B}_1$, $\text{B}_2$, $\text{B}_3$, $\text{B}_4$ |
| $R_4$ | $\text{B}_1$, $\text{B}_2$, $\text{Z}$ | $\text{NB}_4$, $\text{NB}_3$, $\text{NB}_2$, $\text{NB}_1$, $\text{Z}$, $\text{B}_1$, $\text{B}_2$, $\text{B}_3$, $\text{B}_4$ |
| $R_5$ | $\text{B}_1$, $\text{B}_2$, $\text{B}_3$, $\text{Z}$ | $\text{NB}_4$, $\text{NB}_3$, $\text{NB}_2$, $\text{NB}_1$, $\text{Z}$, $\text{B}_1$, $\text{B}_2$, $\text{B}_3$, $\text{B}_4$ |
| $R_6$ | $\text{B}_1$, $\text{B}_2$, $\text{B}_3$, $\text{B}_4$, $\text{Z}$ | $\text{NB}_4$, $\text{NB}_3$, $\text{NB}_2$, $\text{NB}_1$, $\text{Z}$, $\text{B}_1$, $\text{B}_2$, $\text{B}_3$, $\text{B}_4$ |
| $R_7$ | $\text{B}_1$, $\text{B}_2$, $\text{B}_3$, $\text{B}_4$, $\text{Z}$ | $\text{NB}_4$, $\text{NB}_3$, $\text{NB}_2$, $\text{NB}_1$, $\text{Z}$, $\text{B}_1$, $\text{B}_2$, $\text{B}_3$, $\text{B}_4$ |

The Mamdani reasoning method is adopted in fuzzy reasoning. The area center method was used to eliminate mold gelatinization.
5. Simulation Analyses

In order to verify the validity of the preview-fuzzy control method, the track irregularity excitation is used as preview information. The 17 degree of freedom vertical dynamics model based on magnetorheological damper is established. The preview-fuzzy control based on MR damper is applied to the vertical vibration control of high-speed railway vehicle suspension. MatLab/Simulink software environment is used for simulation analysis. The simulation process is shown in Figure 5.

In the simulation, the track irregularity input adopts the six-level track spectrum of the United States, and the triangular series method is used to simulate the time-domain characteristics of the track random irregularity. The vehicle running speed is 300 km/h. The New-Mark compensation method is used to solve the state equations. The Bouc_Wen cubic modified model is adopted for MR damper. In order to analyze and compare the effects of preview control, fuzzy control and preview-fuzzy control, a 17-DOF vertical preview control and a simple fuzzy control model based on MR damper are established. The simulation results of control effect are shown in Figure 6 and Figure 7.

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The simulation results of Figure 6 and Figure 7 show that preview-fuzzy control can effectively reduce the time-domain response of vertical vibration of locomotive bogies. Compared with simple fuzzy control and simple preview control strategy, preview-fuzzy control strategy can better suppress the vertical vibration of vehicle system. It can provide more effective and timely control for external excitation. Therefore, the preview fuzzy control strategy can improve the safety and stability of driving to a certain extent.

6. Conclusions

In this paper, after analyzing the importance of vibration control and the necessity of delay prevention in vehicle dynamics system, combined with the characteristics of MR damper, a preview-fuzzy control strategy based on MR damper is proposed. Through a lot of numerical simulation analysis, the results
show that compared with the simple fuzzy control strategy, the preview-fuzzy control strategy based on MR damper can significantly reduce the vertical vibration of suspension system. Compared with the preview control, the preview-fuzzy control strategy based on MR damper can restrain the external excitation more effectively and alleviate the problem caused by time delay to a certain extent. The preview-fuzzy control strategy based on MR damper has good application value for vibration control of high-speed railway vehicles.

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