Control performance evaluation of railway vehicle MR suspension using fuzzy sky-ground hook control algorithm

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Abstract. This paper presents control performance evaluation of railway vehicle featured by semi-active suspension system using magnetorheological (MR) fluid damper. In order to achieve this goal, a nine degree of freedom of railway vehicle model, which includes car body and bogie, is established. The wheel-set data is loaded from measured value of railway vehicle. The MR damper system is incorporated with the governing equation of motion of the railway vehicle model which includes secondary suspension. To illustrate the effectiveness of the controlled MR dampers on suspension system of railway vehicle, the control law using the sky-ground hook controller is adopted. This controller takes into account both vibration control of car body and increasing stability of bogie by adopting a weighting parameter between two performance requirements. The parameters appropriately determined by employing a fuzzy algorithm associated with two fuzzy variables: the lateral speed of the car body and the lateral performance of the bogie. Computer simulation results of control performances such as vibration control and stability analysis are presented in time and frequency domains.

1. Introduction
The high speed railway vehicle would cause car body vibration which may induce the various problems such as ride stability, ride quality and track abrasion. Thus the vibration control of high speed railway vehicle is necessary for the improvement of vibration control of car body. In general, the suspension systems of railway vehicle have been proposed depending upon the operation mode: passive, active and semi-active. A passive railway vehicle suspension featuring spring, oil damper and pneumatic damper provides design simplicity, but performance limitations are inevitable in the relatively wide frequency range. The active one generally provides high control performance in wide frequency range. Therefore, many researchers have been proposed active suspension technology for railway vehicle which is utilized by oil valve and pneumatic actuators. However, it requires high power source. And active control suspension would need mechanical power into the system, so the stability of the control system needs to be carefully considered. On the other hand, the semi-active suspension offers desirable performance generally enhanced in the active mode without requiring large

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power sources and expensive hardware. Furthermore, various semi-active suspension system featuring magnetorheological (MR) fluid have been proposed and successfully applied in the real field, especially in wheel based passenger vehicle suspension system [1, 2]. These previous works have been focused on the effectiveness for vibration control of a MR damper by just implementing exiting control schemes such as sky-hook controller. In general, railway vehicles are exposed to severe working environment at the high speed working. Therefore, high performance suspension systems are required for railway vehicle [3].

Therefore, in this research, the feasibility for improving the vibration control of railway vehicle featuring semi-active suspension system using MR fluid damper was investigated. Firstly, the MR damper system is designed which is incorporated with the governing equation of motion of the railway vehicle which includes secondary suspension. A nine degree of freedom model for a railway vehicle featuring MR damper is established by the fuzzy sky-ground hook controller. This controller takes account for both vibration control of car body and stability of bogie frame. This is achieved by adopting a weighting parameter between two performance requirements, which is appropriately determined via the proposed fuzzy algorithm. Computer simulations are undertaken in order to demonstrate the effectiveness of the proposed control system.

2. Model of railway vehicle with MR damper
In this section, the mathematical model of MR damper was derived in order to evaluating vibration control performance. The governing equation of motion for the railway vehicle, shown in Figure 1, with suspension systems including MR damper can be derived using Newton’s laws. It is expressed by equation 1. A nine degree of freedom passenger railway vehicle models presented to investigate the lateral response on wheel-set motion to measured data. The wheel-set of the railway vehicle is assumed to follow the track perfectly in the vehicle direction; the wheel-set motion is given by the measured data. A bogie frame’s motions have lateral, yaw and roll according to wheel-set motion. The vehicle equations of motion are presented, including the MR damper force term [3].

\[ M\ddot{x} + C\dot{x} + Kx = B_u f + d \]  

where, vector \( x \) is the displacement vectors, respectively. \( f \) is the actuating force of the MR damper. \( M \) is the matrix of the mass. \( C \) is the damping matrix. \( K \) is the stiffness matrix.

In this study, the MR damper is employed the cylindrical damper. The outer and inner pistons are combined to form a MR valve structure which divides the MR damper into two chambers: the upper and lower chambers. These chambers are fully filled with the MR fluid. The floating piston incorporated with gas chamber functions as an accumulator to accommodate the piston shaft volume as it enters and leaves the fluid chamber. Using quasi-static behavior of the damper, the damping force can be expressed as follows:
\[ F_d = P_2 A_p - P_1 (A_p - A_s) \quad (2) \]

where \( A_p \) and \( A_s \) are the piston and the piston shaft effective cross-sectional areas, respectively. \( P_1 \) is the pressure of upper chamber in the damper. \( P_2 \) is the pressure of lower chamber in the damper. The relations between \( P_1 \), \( P_2 \) and the pressure in the gas chamber, \( P_a \), can be expressed as follows:

\[ P_2 = P_a; \quad P_1 = P_a - \Delta P \quad (3) \]

where \( \Delta P \) is the pressure drops of MR fluid flow through the valve structure. By neglecting minor loss of MR fluid flow, the pressure drops \( \Delta P \) can be calculated as follows:

\[ \Delta P = \frac{6\eta L}{\pi^2 R_d} (A_p - A_s) \dot{x}_p + 2c \frac{L_p}{t_d} \tau_y \quad (4) \]

where \( \tau_y \) is the yield stress of the MR fluid induced by the applied magnetic field, \( \eta \) is the post-yield viscosity of the MR fluid, \( L \) is the length of the inner piston, \( L_p \) is the length of the magnetic pole, \( R_d \) and \( t_d \) are the average radius and gap of the annular duct (the MR valve orifice). The coefficient \( c \) depends on the MR flow velocity profile which can be approximately estimated 1.5 to 1.7 where \( Q \) is the flow rate of MR fluid flow through the valve orifice. The pressure in the gas chamber can be calculated as follows:

\[ P_a = P_0 \left( \frac{V_0}{V_0 + A_s x_p} \right)^\gamma \quad (5) \]

where \( P_0 \) and \( V_0 \) are initial pressure and volume of the accumulator. \( \gamma \) is the coefficient of thermal expansion which is ranging from 1.4 to 1.7 for adiabatic expansion. Using Eq. (2), (3), (4) and piston velocity, the MR damping force can be calculated by [4]

\[ F_{MR} = P_a A_s + (A_p - A_s) \frac{2cL_p}{t_d} \tau_y \text{ sgn}(\dot{x}_p) \quad (6) \]

The first term in Eq.(6) represents the elastic force from the gas compliance and the last one is the force due to the yield stress of the MR fluid which can be continuously controlled by the magnetic field across the MR fluid duct. In this work, the commercial MR fluid (RMS technology) is used. The induced yield stress of the MR fluid can be approximately estimated by

\[ \tau_y = \alpha H^\beta \quad (7) \]

where \( \alpha \) and \( \beta \) are intrinsic values of the MR fluid to be experimentally determined.

3. Design of control algorithm

The MR damper is semi-active system, it is easily expected that the performance of vibration control of the vehicle motion may be deteriorated if excessive noncontrolled magnetic fields are applied to the MR damper. Thus, it is necessary to use appropriate control scheme to achieve satisfactory control performance for various disturbance. One of the most general control strategies for semi-active suspension system is the sky-hook controller proposed by Karnopp et al. [5]. The structure of this control is simple, and hence easy to experimentally realize. However, this controller takes accounts for only ride comfort of vehicle systems. As the railway vehicle, in general, requires the ride comfort as well as the stability to increase vehicle speed. In order to achieve this control target, a new fuzzy sky-ground hook controller is adopted in this work [6]. Unlike the conventional sky-hook controller, the proposed one consists of two ideal dampers; one is fixed to the ceiling while the other fixed to the ground. The fixed one to the ceiling produces a damping force to control the vibration of the bogie.
frame. Therefore, we may improve both the ride quality and the stability by properly adjusting each component of the damping force. To do this, by assuming independent motion of each bogie frame, the following controller was proposed for each bogie frame.

\[ u_{Di} = -\sigma_i c_{sky} V_i - (1 - \sigma_i) c_{ground} V_i \]  

(8)

where, \( c_{sky} \) is the sky-hook control gain, \( c_{ground} \) is the ground-hook control gain, \( \sigma_i \) \((0 \leq \sigma_i \leq 1)\) is the weighting parameter between two control input. Figure 2 shows the block-diagram of the proposed

**Figure 2.** Block diagram for fuzzy sky-ground hook control algorithm.

**Figure 3.** Vibration control results of a car body.

**Figure 4.** Results of fuzzy sky-ground hook controller.
fuzzy sky-ground hook control system. The basic configuration of the fuzzy logic composes three components: a fuzzyfication interface, a decision-making logic and a defuzzyfication interface.

4. Performance evaluation of vibration control

For the computer simulation in a subsequent section, the membership functions are adopted by triangular versions. And the fuzzy parameter values are used by 0.1 to 1. Figure 3 presents control response of the car body when the vehicle speed 180 km/h. We are clearly shown that the acceleration power spectral densities (PSD) of the lateral and roll motion are decreased in the primary frequency ranges. As shown in Figure 4 (a) and 4 (b), the time response of sky-hook control algorithm and fuzzy sky-ground hook control algorithm with the same control input. Figure 4 (a) presents the lateral displacement of bogie frame. It is shown that the proposed fuzzy sky-ground hook is decreased vibration of bogie frame.

5. Conclusion

In this work, a semi-active suspension system with MR dampers of railway vehicle has been investigated by considering a lateral response railway vehicle model, which includes three vibration motions such as lateral, yaw and roll of the car body. To illustrate the feasibility and effectiveness of controlled MR dampers on railway vehicle suspension system, the fuzzy sky-ground hook controller was utilized. This controller takes account for both vibration reduction of car body and increasing stability of bogie frame. In order to demonstrate the effectiveness of the proposed control system, computer simulation is undertaken showing vibration control performances. It has been demonstrated that both vibration control and stability can be improved by employing the proposed control system associated with MR damper.

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