Feature Article

Simulation and Experimental Study on the Active Stability of High-Speed Trains

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***Abstract*—An active hunting stability scheme is proposed for the high-speed trains based on frame lateral vibration control. The stability of the vehicle is improved by exerting active control force on the front and rear frames of the bogie. First, a simplified lateral vibration model of a single bogie is established to the control system design. The feedback gain matrix is obtained according to the linear quadratic optimal control theory. Then, the multibody dynamics model of the vehicle is built using SIMPACK, and the linear stability and straight running performance are analyzed under different working configurations. Finally, the active control effects are verified by a scaled roller rig. The results show that this active control scheme to improve the stability performances of vehicles through the feedback of frame vibration state is feasible.**

Various active control systems have been researched in the last two decades to influence the vehicle's dynamic behavior under different working conditions, with the goals of improving the lateral stability or curving performance of the vehicle, meanwhile attenuating the vibration energy of the carbody, etc.[1,2] At present, the design of control systems for high-speed vehicles mainly focuses on primary and secondary suspensions. Many scholars have studied the active control schemes on primary suspension, which has a significant impact on the vehicle stability. Pearson studied the effect of optimal control and classical control strategies on actively stabilized wheelsets of a high-speed vehicle. A roller rig was used to compare the lateral stability of vehicles with active control

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and passive suspension at 300 km/h, indicating that active control can reduce wheelset lateral displacement.[3] Bideleh *et al.* designed a robust controller applying a yaw torque to the wheelset for a high-speed train bogie and corrected the delay output of the actuators using a second-order polynomial extrapolation.[4] Mei *et al.* proposed a control method based on the concept of absolute stiffness (skyhook spring) to improve the wheelset stability. The simulation results show that the control effect is proportional to the yaw movement of the wheelset.[5]

However, there are certain risks in the actual process due to the direct application of active control onto a wheelset. If the control system is abnormal, the dynamic behavior of the vehicle may be deteriorated or even unstable. Therefore, there are also control schemes combined with the secondary suspension. Conde Mellado *et al.* proposed an active lateral suspension including pneumatic actuators connected to the secondary suspension air springs, which effectively reduces the lateral acceleration of the vehicle body in curve negotiation and improves the ride comfort.[6] Orukpe studied the application of model predictive control technology using hybrid H2/H∞ method on railway vehicles, aiming to improve their ride quality.[7] Anneli *et al.* used a full-size rail vehicle model to study how to improve the lateral comfort of the vehicle by implementing H∞ and skyhook damping control strategies.[8] Zhou *et al.* proposed a control method for high-speed tilting train combining tilting with active lateral secondary suspension. The active lateral secondary suspension was used to attenuate the vehicle lateral vibration energy on straight track, while compensating the tilting motion of the vehicle on curve.[9] Qazizadeh *et al.* conducted on-track tests of running comfort for high-speed vehicle with active vertical secondary suspension.[10] There were also other active control methods applied to the railway vehicle. Yao *et al.* proposed some indirect control methods for high-speed motor trains using different control strategies to improve vehicle dynamic performances.[11–14] Three different frame vibration control configurations were compared in terms of their performances in improving the lateral stability of a high-speed train bogie and two active control methods by applying a lateral force to the traction motor were proposed and their effects on vehicle dynamics were analyzed.

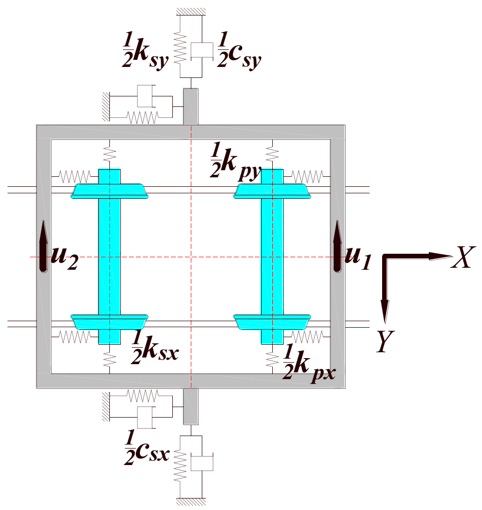

Figure 1. Frame lateral vibration model.

In this paper, an optimal control scheme is proposed for high-speed trains based on frame lateral vibration control. This scheme regards the front and rear bogies of the vehicle as a whole, and changes the motion state of the bogie by applying active control force to the front and rear two frames, which avoids a significant modification of the bogie structure. The control objective is to improve the lateral stability, meanwhile reducing the track shift force on straight track. In the simulation, the influence of optimal control theory on improving vehicle linear stability and straight running performance is analyzed under four different cases. Finally, a scaled roller rig is used to verify the effect of optimal control on improving stability.

FRAME LATERAL VIBRATION MODEL

In fact, the vibration state of the front and rear bogies is similar. In this and next section, the vibration of a single bogie is discussed. The lateral vibration model consisting of two wheelsets, one bogie frame is considered for the optimal control design, is shown in Figure 1. The bogie frame is connected to the intrinsic coordinate system of the vehicle body by the secondary suspension consisting of longitudinal

Table 1. Bogie model parameters.

Symbol	Definition	Value
m_f	Mass of bogie frame	2328 kg
I_f	Yaw inertia of bogie frame	4080 kg·m^2
k_{px}	Longitudinal stiffness of primary suspension per axle	0.92 kN/mm
k_{py}	Lateral stiffness of primary suspension per axle	0.92 kN/mm
k_{sx}	Longitudinal stiffness of secondary suspension per axle	0.133 kN/m
k_{sy}	Lateral stiffness of secondary suspension per axle	0.133 kN/m
c_{sx}	Yaw damper damping	0.33 MN·s/m
c_{sy}	Lateral damper damping of secondary suspension	15 kN·s/m
$2l_1$	Longitudinal spacing of primary suspension	2000 mm
$2l_a$	Longitudinal spacing of actuator	2900 mm
2l	Wheel base	2500 mm
$2b_1$	Lateral spacing of primary suspension	2000 mm
$2b_2$	Lateral spacing of secondary suspension	1900 mm

and lateral springs and dampers, where the lateral displacement of the vehicle body is predetermined. The frame is connected to the solid wheelsets by the primary suspension consisting of longitudinal and lateral springs. The frame and wheelset have two degrees of freedom in the model, including yaw and lateral movements. Due to the difficulties in lateral displacement measurement of the wheelset and controllability and observability of the entire control system, in this study, the lateral and yaw motions of the wheelset are not set as the state variables of the system and the wheel–rail force caused by those is considered as the external excitation of the system.

The equations of motions of the bogie are given as follows:

$$\begin{aligned} &m_f\ddot{y}_f + c_{sy}\dot{y}_f + (2k_{py} + k_{sy})y_f \\ &\quad = u_1 + u_2 + k_{py}(y_{w1} + y_{w2}) \end{aligned} \tag{1}$$

$$\begin{aligned} &I_f\ddot{\varphi}_f + b_2^2 c_{sx}\dot{\varphi}_f + (2l_1^2 k_{py} + 2b_1^2 k_{px} + b_2^2 k_{sx})\varphi_f \\ &\quad = l_a(u_1 - u_2) + l_1 k_{py}(y_{w1} - y_{w2}) \\ &\qquad + b_1^2 k_{px}(\varphi_{w1} + \varphi_{w2}). \end{aligned} \tag{2}$$

Rewrite the above equations into a matrix form

$$\mathbf{M}\ddot{\mathbf{x}} + \mathbf{C}\dot{\mathbf{x}} + \mathbf{K}\mathbf{x} = \mathbf{E}\mathbf{u} + \mathbf{T} \tag{3}$$

where (1) and (2) represent the lateral and yaw movements of the bogie, respectively. for $\mathbf{x} = [y_f, \varphi_f]^{\mathrm{T}}$, the states y_f, φ_f are the lateral displacement and yaw angle of frame. The matrices **M**, **C**, and **K**, are the mass, damping, and stiffness components of the system, respectively. The matrix **T** is the external excitation of the system caused by the lateral and yaw motion of the wheelsets. The control force matrix **u** represents the output force generated by the actuator and applied to the front and rear end beams of frame.

The state equation of the bogie control system can be written as

$$\begin{aligned} \dot{\mathbf{x}}(t) &= \mathbf{A}\mathbf{x}(t) + \mathbf{B}\mathbf{u}(t) + \mathbf{F}(t) \\ \mathbf{y}(t) &= \mathbf{D}\mathbf{x}(t). \end{aligned} \tag{4}$$

The state vector is defined as

$$\mathbf{x} = \begin{bmatrix} y_f & \varphi_f & \dot{y}_f & \dot{\varphi}_f \end{bmatrix}^{\mathrm{T}}. \tag{5}$$

The matrices and vectors of the frame motion equation are listed

$$\mathbf{A} = \begin{bmatrix} 0_{2\times2} & \mathbf{I}_{2\times2} \\ -\mathbf{M}^{-1}\mathbf{K} & -\mathbf{M}^{-1}\mathbf{C} \end{bmatrix} \quad \mathbf{B} = \begin{bmatrix} 0_{2\times2} \\ \mathbf{M}^{-1}\mathbf{E} \end{bmatrix}$$

$$\mathbf{F} = \begin{bmatrix} 0_{4\times1} \\ \mathbf{M}^{-1}\mathbf{T} \end{bmatrix} \quad \mathbf{E} = \begin{bmatrix} 1 & 1 \\ l_a & -l_a \end{bmatrix}$$

$$\mathbf{T} = k_{py}\begin{bmatrix} y_{w1} + y_{w2} \\ l_1(y_{w1} - y_{w2}) + b_1^2(\varphi_{w1} + \varphi_{w2}) \end{bmatrix}.$$

The values and definitions of system parameters are listed in Table 1.

OPTIMAL CONTROL DESIGN

Optimal control is the control method that optimizes system performance under specific constraints and control requirements, which is one of the most widely used methods in active control of mechanical engineering.[15,16] In this paper, the above model is controlled by the linear quadratic optimal control theory. According

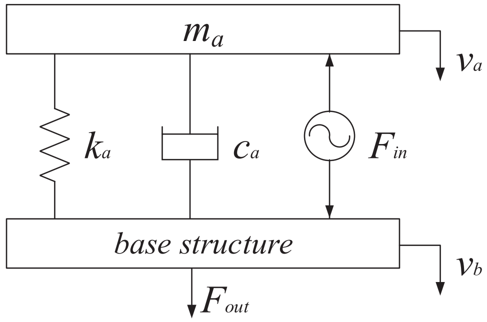

Figure 2. Dynamics model of inertial actuator.

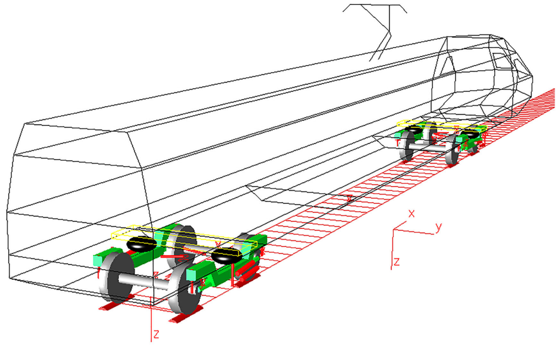

Figure 3. Vehicle dynamic model.

to the theoretical analysis, the control vector $\mathbf{u}$ can obtain the optimal solution by the following formula:

$$J = \frac{1}{2}\int_0^{\infty} (\mathbf{x}^{\mathrm{T}} Q \mathbf{x} + \mathbf{u}^{\mathrm{T}} R \mathbf{u}) dt \tag{6}$$

where $\mathbf{Q}$ and $\mathbf{R}$ are matrices of weight coefficients, which represent the contribution of system vibration energy and actuator input energy to the control system, respectively. In order to achieve the desired system performance such as smaller lateral displacement of the bogie frame, the matrices $\mathbf{Q}$, $\mathbf{R}$ need to be continuously debugged. Here, $\mathbf{Q}$, $\mathbf{R}$ matrices are

$$\mathbf{Q} = \begin{bmatrix} 1 & & & \\ & 1e4 & & \\ & & 1 & \\ & & & 1e4 \end{bmatrix} \mathbf{R} = \begin{bmatrix} 1e-7 & \\ & 1e-7 \end{bmatrix}.$$

The output force of the actuator is obtained by the following equations:

$$\mathbf{u} = -\mathbf{K}_{\mathrm{out}} \cdot \mathbf{x} = -\mathbf{R}^{-1}\mathbf{B}\mathbf{P} \tag{7}$$

$$\mathbf{PA} + \mathbf{A}^{\mathrm{T}}\mathbf{P} - \mathbf{PBR}^{-1}\mathbf{B}^{\mathrm{T}}\mathbf{P} + \mathbf{Q} = \mathbf{0} \tag{8}$$

where $\mathbf{P}$ is the solution of Riccati equation and the state equations are used to solve (6)–(9) through MATLAB.

According to the paper by Benassi *et al.*,[17] an idealized inertial actuator is applied to control the lateral vibration of the bogie. The actuator dynamics model is shown in Figure 2. Inertial actuators are widely used components in the field of active control of vehicles which are mainly composed of moving mass, permanent magnets, coils, and springs.

The equations describing the dynamics of the moving mass and base structure are given by

$$j\omega m_a v_a + c_a(v_a - v_b) + \frac{k_a}{j\omega}(v_a - v_b) = -F_{\mathrm{in}} \tag{9}$$

$$F_{\mathrm{out}} - c_a(v_a - v_b) - \frac{k_a}{j\omega}(v_a - v_b) = F_{\mathrm{in}} \tag{10}$$

where v_a and v_b are the vibrational velocity of the moving mass and the base structure, respectively. F_{in} and F_{out} are respectively the reaction force generated by the actuator and the control force applied to the base structure.

Substituting (9) into (10)

$$F_{\mathrm{out}} = -j\omega m_a v_a. \tag{11}$$

It is shown that the control force applied to the base structure by the inertial actuator is equal to the inertial force of the moving mass. Considering the magnitude of the output control force applied to the real bogie and the natural frequency of the inertial actuator, a new inertial actuator may need to be redesigned for meeting the actual control requirements.

SIMULATION RESULTS

In this section, a high-speed train including a car body and two power bogies fitted with actuators is modeled in SIMPACK and analyzed different simulation results.

Vehicle Dynamics Model

As shown in Figure 3, the model consists of 17 rigid bodies and includes 50 degrees of freedom. The carbody and the bogie are connected

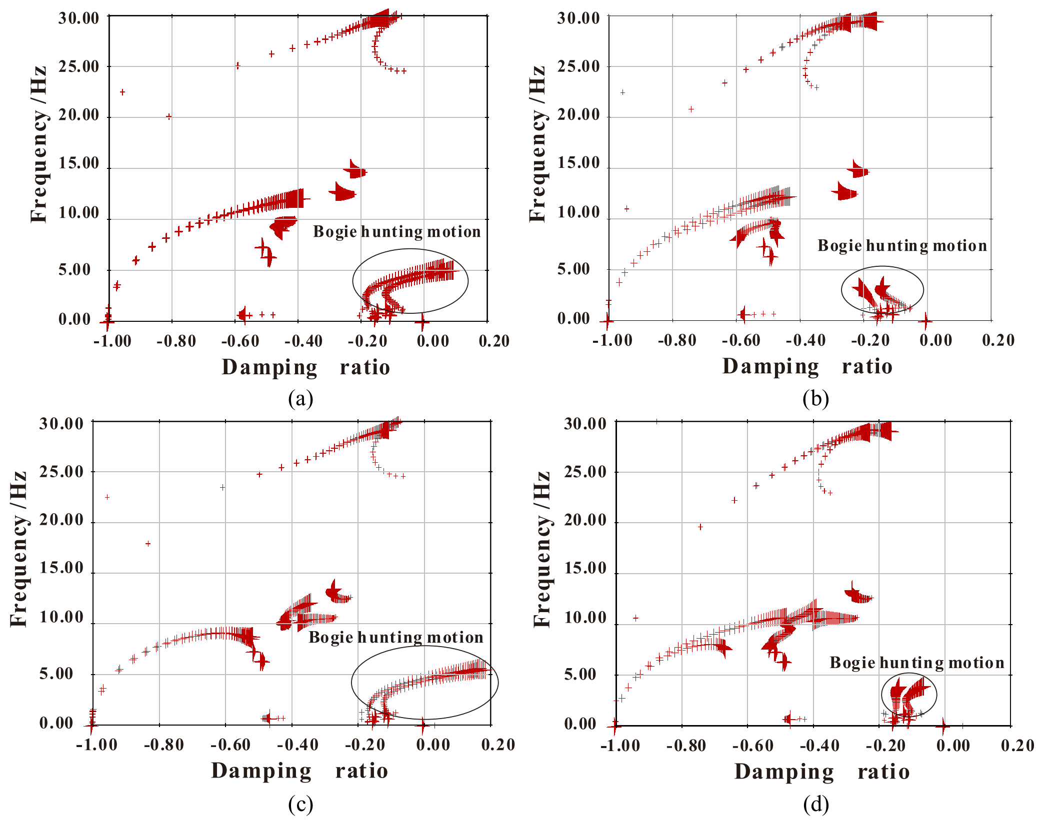

Figure 4. Root locus of the vehicle in different cases (new wheel). The four subgraphs correspond to the vehicle root curves in four cases and the circled part indicates the bogie hunting motion. The horizontal axis represents the damping ratio of the motion mode. When the damping ratio is greater than 0, the corresponding motion is considered unstable. (a) Uncontrolled. (b) Control. (c) Uncontrolled and yaw damper fault. (d) Control and yaw damper fault.

by the secondary suspension, which includes two air springs, four yaw dampers, two lateral dampers, and two vertical dampers. The frame and the wheelsets are connected via the primary suspension, which includes the coil springs and vertical damper. The parameters of the vehicle dynamics model are derived from Table 1. In order to highlight the effect of optimal control on improving vehicle dynamics performance, four cases are considered in this section: 1) Uncontrolled and normal operating condition; 2) optimal control and normal operating condition; 3) uncontrolled and fault condition (yaw dampers fault in the front and rear bogies); 4) optimal control and fault condition.

Linear Stability

To verify the impact of optimal control on vehicle stability, the root locus method is used to analyze the motion modes of the vehicle at different speeds. During the calculation, the linearized wheel profiles are adopted to include the new and the worn wheel. Figures 4 and 5 show the results of the root locus curve of the vehicle with different wheel profiles, in which the speed ranges from 20 to 1000 km/h (20 km/h steps) and each "+" represents a corresponding eigenvalue. For the above-mentioned root locus curve, the vertical axis represents the frequency of the motion mode, and the horizontal axis represents the damping ratio of the motion mode (the smaller the damping ratio is, the more stable the motion mode is). When the damping ratio is greater than 0, the corresponding motion is considered unstable. Since the damping ratio of the bogie hunting mode is relatively close to 0, the vehicle instability determined by the bogie hunting motion (low-frequency mode, less than 5 Hz).

In Figure 4, subgraph (a) shows the root locus of the vehicle in case (1), where the linear

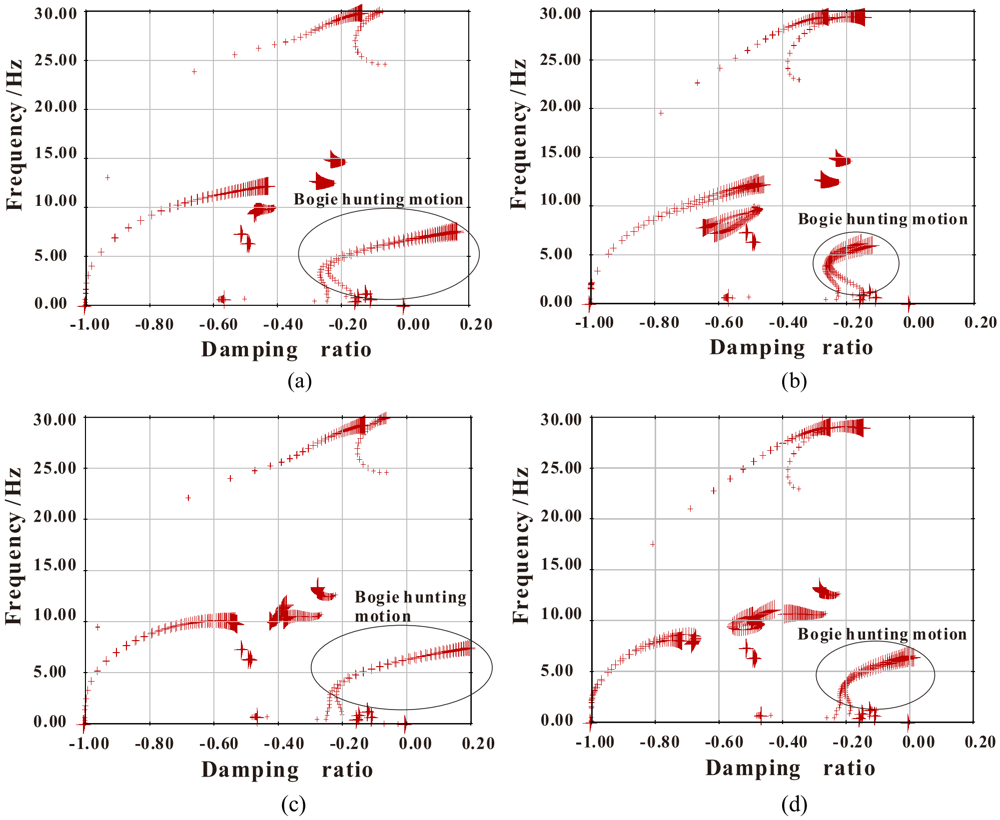

Figure 5. Root locus of the vehicle in different cases (worn wheel). The four subgraphs correspond to the vehicle root curves in four cases and the circled part indicate the bogie hunting motion. The horizontal axis represents the damping ratio of the motion mode. When the damping ratio is greater than 0, the corresponding motion is considered unstable. (a) Uncontrolled. (b) Control. (c) Uncontrolled and yaw damper fault. (d) Control and yaw damper fault.

critical speed of the vehicle is 640 km/h and subgraph (b) shows the root locus of the vehicle in case (2). When the speed is inferior to a certain value, the damping ratio of the bogie hunting mode decrease improves the linear stability compared with case (1) with increasing speed. Subgraph (c) shows the root locus diagram of the vehicle in case (3). Due to the failure of the yaw damper, the hunting motion of the bogie cannot be effectively suppressed and the stability of the vehicle is significantly lower than case (1), where the linear critical speed of the vehicle is 480 km/h. Subgraph (d) shows the root locus of the vehicle in case (4). The output force of the actuator effectively suppresses the bogie hunting motion, which significantly improves the linear stability compared with case (3).

The results of the root locus curve of the vehicle with worn wheel profiles under four cases are shown in Figure 5, which reflects a similar behavior compared with Figure 4. Subgraph (a) shows the root locus of the vehicle in case (1). Due to the increment of the equivalent conicity of the wheelset, the linear stability is significantly worse compared to the vehicle with new wheel profile, where the linear critical speed of the vehicle is 520 km/h. Subgraph (b) indicates that the linear stability of the vehicle is improved after the optimal control. Subgraph (c) shows the root locus of the vehicle in case (3), where the linear critical speed of the vehicle is 400 km/h. Subgraph (d) shows that the optimal control effectively suppresses the bogie hunting motion and improves the stability of the vehicle. At this time, the linear critical speed of the vehicle is 880 km/h.

Comparing the above root locus curve, when the running speed of the vehicle is in a lower range, the damping ratio of bogie hunting mode is basically the same before and after control,

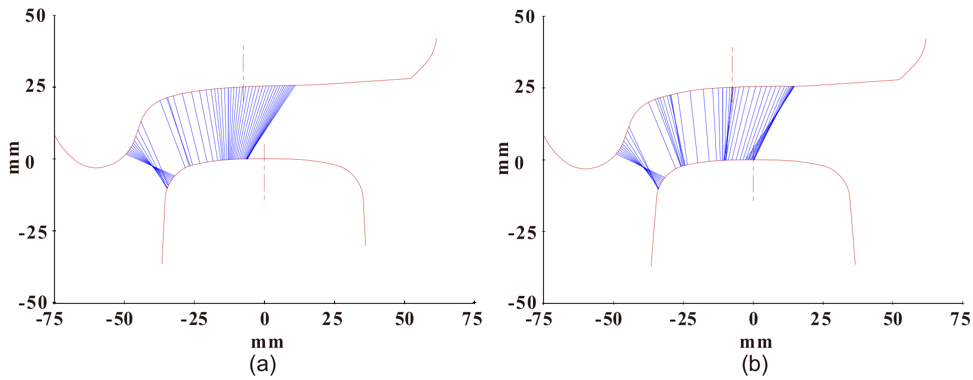

Figure 6. Contact point connections wheel and rail. The two subgraphs correspond to the two kinds of wheel treads including new wheel and worn wheel. (a) New wheel. (b) Worn wheel.

which indicates the optimal control does not work. However if the speed is in the higher range, the damping ratio will reduce after the control, which demonstrates the optimal control effectively suppresses the bogie hunting, thereby improving the vehicle stability. It should be noted that the control effect is more obvious under high speed and fault conditions.

Running Performances on Straight Track

The running performances on straight track of the vehicle with two kinds of wheel treads at 350 km/h are investigated in nonlinear analyses. The wheel and rail profile information are shown Figure 6, and the real measurement data from Wu-Guang high-speed line is applied to the model as track irregularity.

In Figure 7, subgraph (a) shows the track shift force of the rear wheelset of rear bogie in new wheel which is the largest in four wheelsets. According to the simulation results shown in case (1) and (2), the optimal control does not work. In case (3), due to the failure of the yaw damper, the track shift force is significantly increased compared with case (1). In case (4), the track shift force is significantly reduced and is close to the case (1) since the optimal control suppresses the bogie hunting. Subgraph (b) shows the track shift force of the rear wheelset with worn tread in four cases, which reflects the behavior similar to subgraph (a). Due to the rise of the equivalent conicity, the track shift force is increased compared with the new wheel tread and is significantly reduced after the optimal control under the fault condition. Subgraph (c) shows the output force of the first actuator of the rear bogie with new wheel, which outputs the maximum control force in the four actuators. In case (2) and (4), the output force of the actuator is basically within 10 kN. Subgraph (d) shows the output force of the corresponding actuator, which reflects the behavior similar to subgraph (c).

Further, starting from an initial value of 200 km/h, the vehicle speed is increased by 50 km/h wide discrete steps and the track shift force of the vehicle is studied (shown in Figure 8). The track shift force shows the same trend, which means that the optimal control has similar effects on vehicle with the new or the worn wheel. When the vehicle is running under normal condition and the speed is lower than 400 km/h, the track shift force of the vehicle before control is less than that after control, and the difference of the track shift force is reduced with the increase of the speed. When the speed is higher than 400 km/h, the optimal control can reduce the track shift force. It can be seen that a similar pattern to the track shift force under fault condition. When the speed is higher than 300 km/h, the optimal control can effectively reduce the track shift force and the control effect is obvious as the operating speed increases.

The optimal control does not play a role in reducing the track shift force in the low speed range. The possible reason is that the vehicle suspension parameters are optimized mainly for the low speed. At this time, the control is equivalent to increasing the original stiffness and the damping value, resulting in no improvement or even deterioration in vehicle dynamics behavior. When

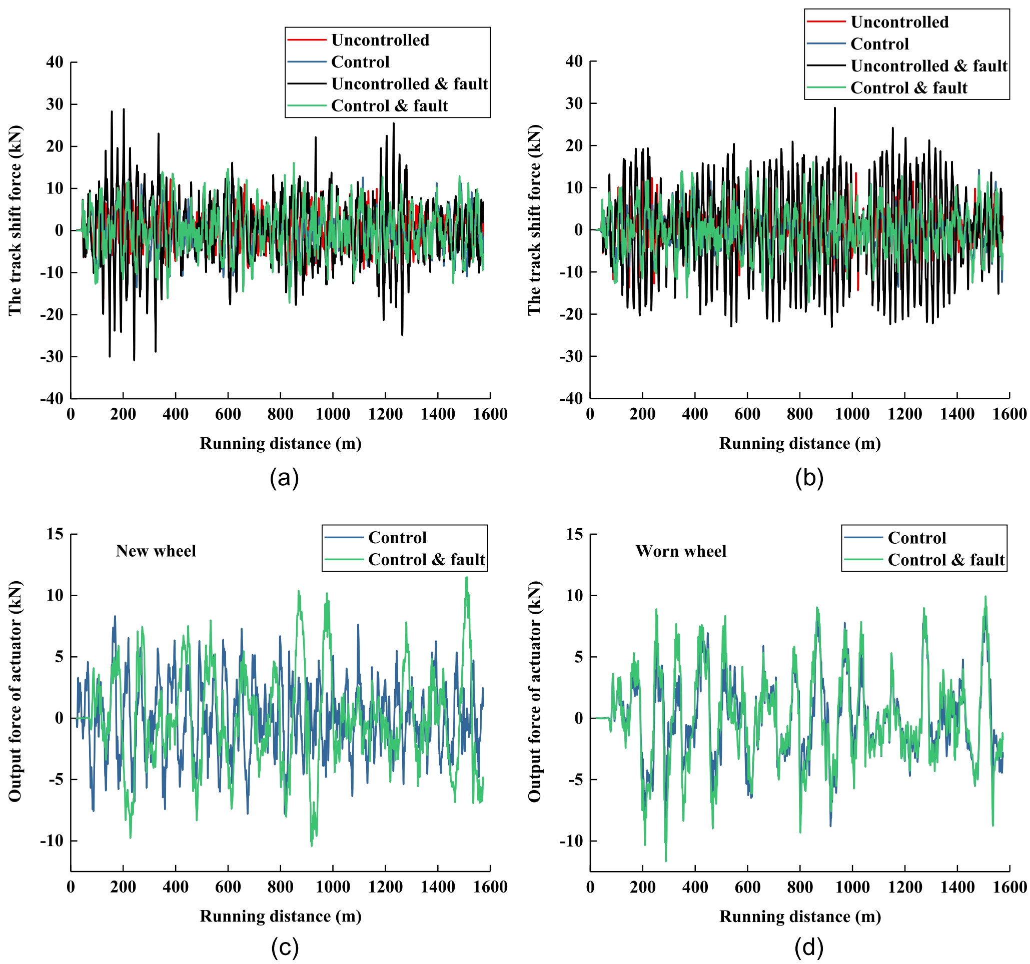

Figure 7. Time-domain analysis results with two kinds of wheel on straight track. Four subgraphs correspond to the track shift force of the rear wheelset and the output force of the actuator. (a) Track shift force (new wheel). (b) Track shift force (worn wheel). (c) Output force of the actuator (new wheel). (d) Output force of the actuator (worn wheel).

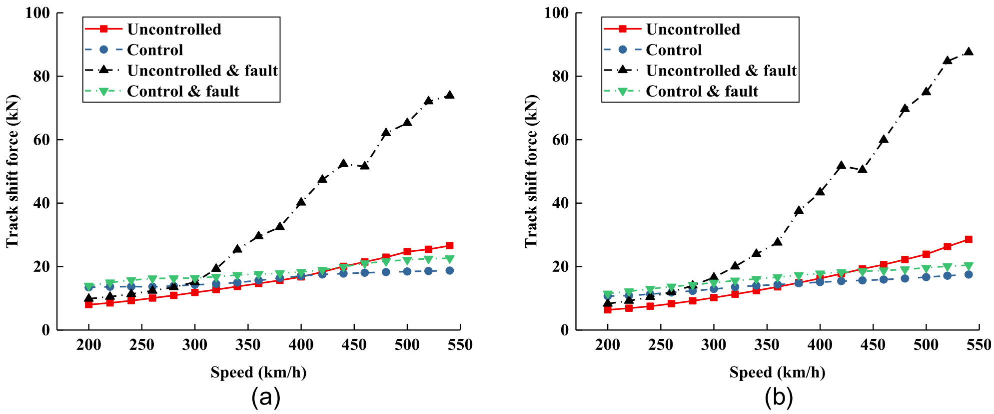

Figure 8. Effect of running speed on the track shift force under different cases with two kinds of wheel treads. (a) Track shift force (new wheel). (b) Track shift force (worn wheel).

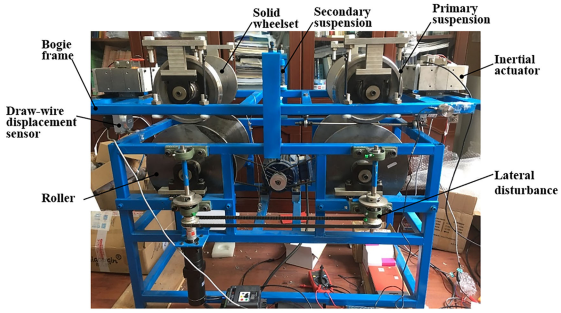

Figure 9. Configuration of the roller rig.

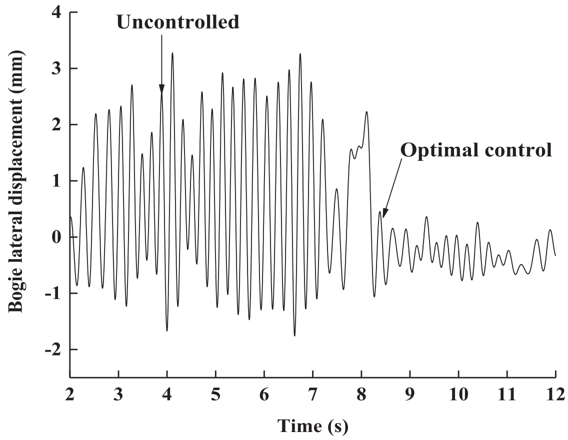

Figure 10. Lateral displacement of the bogie. In 2–8 s, the bogie is in an unstable state. In 8–12 s, the stabilization is achieved by applying the output force of the inertial actuator.

the vehicle is running at high speed, the optimal control can suppress the hunting movement of the bogie compared with the original suspension, thus, improving the vehicle dynamic performance.

TEST RESULTS

In order to verify the improvement of vehicle dynamics performance under optimal control, in this section, a scaled roller rig is applied for testing in Southwest Jiaotong University.[18] Figure 9 shows the configuration of the scaled roller rig, which includes the mechanical structure and the control module. The mechanical structure includes a bogie frame, rollers, solid wheelsets, lateral excitation, primary, and secondary suspensions. The control module includes two draw-wire displacement sensors, two straight rod displacement sensors, a controller, two drivers, and two inertial actuators. The draw-wire displacement sensors and the straight rod displacement sensors are used to measure the lateral displacement of the bogie and actuator, respectively, which are placed on the front and rear beams of the bogie. The control signal is emitted by the controller and passed through the driver to the actuator. When the rotational speed of the wheel increases, the bogie loses stability with the increase of the frame displacement. At this point, the control starts, and the vibration of the bogie is stable with the reciprocating linear motion of the inertia actuators. Figure 10 shows the lateral displacement of the bogie before and after control. Considering that there may be deviations in the spring stiffness, the lateral displacement of the bogie is not symmetrically distributed. After optimal control, the bogie displacement is significantly reduced and consistent with the simulation results.

CONCLUSION

1. In this study, a control scheme is proposed for improving the active hunting stability of high-speed train through the linear quadratic optimal control theory, in which inertial actuators act on the front and rear end beam of frame and exert active control force on the front and rear bogies. Considering controllability and observability of the control system, only four measurements of motion of bogie frame are set as the state variables including the lateral displacement and yaw angle and their first derivatives of frame. Simulation and experimental results show that the control scheme can effectively improve the hunting stability and the dynamic behavior.
2. Comparing the linear stability of the vehicle in four cases including yaw dampers fault in the front and rear bogies, it is found the root locus of bogie low-frequency hunting mode determining the vehicle critical speed is different. When the speed in the higher range, the active control can effectively suppress the bogie hunting motion as the speed increases. When the speed in the lower range, the root locus of the bogie movement are basically the same before and after the control, which indicates the optimal control does not work at this time. Optimal control is more effective in high-speed and fault conditions.

3. Comparing the running performances on straight track of the vehicle in four cases, the track shift force is basically the same before and after the control under normal condition. Under the fault condition, the optimal control can effectively reduce the track shift force and in addition, the effect of optimal control on reducing the track shift force is related to the running speed of the vehicle.

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