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Research on the Comfort of the Straddle Type Monorail Train - Flexible Track Beam System

Huping Lu, Kaikai Song, Wangjian Che

School of Mechanical and Electrical Engineering,GANSU FORESTRY VOCTECH UNIVERSITY,Tianshui, Gansu, 741020

ABSTRACT

The coupling vibration problem of the straddle type monorail-flexible track beam system is very complex, involving numerous sensitivity factors, and many issues need further research. The safety and comfort of the dynamic operation of the formation train are crucial for the safe operation of the rail vehicle. Based on the multi-body dynamics theory and Timoshenko beam theory, this paper derives the dynamic models of the straddle type monorail train and the flexible track beam respectively. At the same time, the tire model is accurately considered, and a refined coupling dynamic model of the straddle type monorail flexible track beam is established. We studied the comfort performance of the coupling system between a straddle type monorail train and a flexible track beam under the influence of factors such as track roughness and support parameters, and evaluated the calculation results based on the comfort evaluation system constructed in this paper. This provides theoretical support for the safety design and vibration control of the coupling system between the straddle type monorail train and flexible track beam.

KEYWORDS

Coupling dynamic model of train-flexible track beam; Track irregularity; Support parameters; Comfort performance

1 Introduction

The vibration problem of flexible track beam structure is one of the main factors affecting the dynamic operation safety of monorail trains [1-2]. At present, the research focus on the coupling vibration problem between the straddle type monorail train and flexible track beam bridge at home and abroad is on the static problem of the elevated track beam structure. The coupling dynamic performance between the train and the flexible track beam is equally important, which is related to the dynamic operation safety and riding comfort of the train. When the assembled train passes through the elevated flexible track beam line at a certain speed, the flexible track beam is subjected to the dynamic load of the assembled train and generates intense vibration. The reciprocating intense vibration can cause fatigue of the elevated flexible track beam structure, thereby reducing the service life of the track beam structure and even causing serious traffic accidents; In addition, the reciprocating vibration of the elevated flexible track beam structure will also have an impact on the dynamic driving safety and vibration stability of the grouped trains; Especially when the natural frequency of the composed train system is close to or equal to the natural frequency of the elevated flexible track beam structure, the coupled system composed of the composed train and the elevated track beam structure will resonate, which will cause more incalculable losses to the coupled system. Therefore, in practical engineering applications and designs, efforts should be made to avoid resonance caused by the natural frequencies of the two being close. Based on the above discussion, a more in-depth study is needed on the dynamic interaction between the train flexible track beam coupling of the straddle type monorail system. Especially the study of the coupled dynamic performance of track trains and flexible track beams under uneven conditions is crucial. With the extensive construction of straddle type monorail transit systems in major cities in China and the increase in traffic volume, the problem of coupled vibration between trains and flexible track beams has become increasingly prominent.

2 Coupling dynamic model of straddle type monorail-train flexible track beam

2.1 Vecicle model

For a single section monorail vehicle, its composition mainly consists of three main components, namely a body and two frames, which are connected by a suspension system (air spring, hydraulic shock absorber). Based on previous research results, it can be known that the expansion and contraction vibrations of the vehicle body and bogie have little effect on the vertical and lateral vibrations of the flexible track beam system. The maximum operating speed of the monorail vehicle does not exceed 80km/h, and the impact of expansion and contraction vibrations is much lower than that of the formation train. Therefore, this article will not consider the expansion and contraction vibrations of each rigid body. To simplify the modeling process of the model in this article; Therefore, the following assumptions are made [3-5]：

(1) For the time being, the elastic deformation effects of the vehicle body, front and rear bogies, and transmission shaft are not considered. They are assumed to be rigid bodies, and the vehicle body is assumed to be a symmetrical rigid body with left and right axes.

(2) Simplify the secondary suspension system (air spring, transverse hydraulic shock absorber) into a nonlinear mathematical model that is parallel to each other, and assume that the running wheels, guide wheels, stabilizing wheels, and elevated flexible track beams are tightly attached together.

(3) Assuming that the train is moving at a constant speed along the elevated flexible track beam, without considering its longitudinal vibration for the time being.

For a single section monorail vehicle, the body and front and rear bogies are considered as rigid bodies, where both the body and front and rear bogies have 2 translational and 3 rotational degrees of freedom, namely the lateral movement, heave, roll, yaw, and nodding movements of the body, as well as the lateral movement, heave, roll, yaw, and nodding movements of the front and rear bogies, totaling 15 degrees of freedom.

The dynamic model of a 15 degree of freedom monorail vehicle is derived and established based on the Lagrange equation (specific derivations have been carried out in references [3] and [4], which can be referred to in the literature and will not be repeated in this article). The motion control differential equation is as follows.

$$M_v\ddot{q}_v(t)+C_v\dot{q}_v(t)+Kq_v(t)=F_v \tag{1}$$

In the formula, M_v、C_v、$K_v$is the mass, damping, and stiffness matrix of the vehicle system; F_v is the load column vectors acting on the vehicle body, front, and rear bogies; $q_v(t)$、$\dot{q}_v(t)$、$\ddot{q}_v(t)$ is the displacement, velocity, and acceleration vectors of the vehicle system.

2.2 Flexible track beam model

The ultimate goal of constructing a refined and reasonable dynamic model for elevated flexible track beams is to serve the dynamic performance characteristics design of elevated flexible track beams. Before conducting the dynamic characteristics analysis of train flexible track beam coupling, it is necessary to first construct a refined dynamic model of the flexible track beam. Most of the elevated flexible track beams in the Chongqing straddle type monorail system are made of simply supported PC concrete beams. As the height of the elevated simply supported beams is much smaller than the length of the track beams, the following assumptions are made in this article[6]:

(1) Ignoring the deformation of the track beam section, the left and right track sections have the same vibration mode.

(2) At present, the flexibility of the track beam bridge pier has not been considered, and the track beam is connected to the ground through elastic supports.

This article takes the single span elevated line of Chongqing's straddle type monorail transit as the research object. The elevated simply supported PC track beam adopts a standard box shaped section of 0.85m × 1.5m. Due to the significant impact of shear and torsional deformation of track beams on the vibration performance of straddle type monorail systems, in order to consider the influence of shear and torsional deformation of flexible track beams, this paper introduces the Timoshenko beam model.

To simulate the dynamic response characteristics and effects of flexible track beam systems. Based on the Timoshenko beam theory, considering the longitudinal, transverse, vertical, Y-direction shear, Z-direction shear, and torsional vibration around the X-axis of a single Timoshenko beam element in a track beam, the dynamic model of a flexible track beam is shown in Figure 2.

The differential equation of the flexible track beam is as follows [7-8]:

$$E_b A_b \frac{\partial^2 X_b}{\partial x^2} - \rho_b A_b \frac{\partial X_b^2}{\partial t^2} = F_X(t)\delta(x - x_w(t)) + \sum_{f\in Q} F_{X_f}(t) \tag{2}$$

$$K_{by} A_b G_b \left(\frac{\partial^2 Y_b}{\partial x^2} - \frac{\partial \theta_b}{\partial x} \right) - \rho_b A_b \frac{\partial^2 Y_b}{\partial t^2} - \rho_b z_b A_b \frac{\partial^2 Y_b}{\partial t^2} = F_Y(t)\delta(x - x_w(t)) + \sum_{f\in Q} \delta(x - x_f) F_{Y_f}(t) \tag{3}$$

$$K_{bz} A_b G_b \left(\frac{\partial^2 Z_b}{\partial x^2} - \frac{\partial \psi_b}{\partial x} \right) - \rho_b A_b \frac{\partial^2 Z_b}{\partial t^2} - \rho_b y_b A_b \frac{\partial^2 \varphi_b}{\partial t^2} = F_Z(t)\delta(x - x_w(t)) + \sum_{f\in Q} \delta(x - x_f) F_{Z_f}(t) \tag{4}$$

$$E_b J_{by} \frac{\partial^2 \psi_b}{\partial x^2} - K_{by} A_b G_b \left(\frac{\partial \psi_b}{\partial x} + \psi_b \right) - \rho_b J_{by} \frac{\partial^2 \psi_b}{\partial t^2} = 0 \tag{5}$$

$$E_b J_{bz} \frac{\partial^2 \theta_b}{\partial x^2} + K_{by} A_b G_b \left(\frac{\partial Y_b}{\partial x} - \theta_b \right) - \rho_b J_{bz} \frac{\partial^2 \theta_b}{\partial t^2} = 0 \tag{6}$$

$$E_b J_{b\varepsilon} \frac{\partial^4 \varphi_b}{\partial x^4} - G_b J_{bx} \frac{\partial^2 \varphi_b}{\partial x^2} - \rho_b J_{b\varepsilon} \frac{\partial^4 \varphi_b}{\partial x^2 \partial t^2} + \rho_b z_b A_b \frac{\partial^2 Y_b}{\partial t^2} - \rho_b y_b A_b \frac{\partial^2 Z_b}{\partial t^2} + \rho_b J_{bp} \frac{\partial^2 \varphi_b}{\partial t^2} = \delta(x - x_w(t)) M_X(t) + \sum_{f\in Q} \delta(x - x_f) M_{X_f}(t) \tag{7}$$

In the formula: E_b、$G_b$represent the elastic modulus and shear modulus of the flexible track beam respectively; ρ_b is the density of flexible track beams; A_b is the cross-sectional area; J_{by}、J_{bz} is the moment of inertia relative to the Y and Z directions; J_{bx} is the Saint Venant torsion constant; $J_{b\varepsilon}$ is the deflection constant of the flexible track beam section; K_{by}、K_{bz} is the shear correction factor for both Y and Z directions; $J_{bp}$is the polar moment of inertia; y_s is the distance in the Y direction between the shear center of the cross-section and the geometric center; y_b、z_b is the distance between the cutting center and the geometric center in the Z and Y directions; $x_\omega(t)$ is the current longitudinal distance of the tire; $F_X(t)$、$F_Y(t)$、$F_Z(t)$、$M_X(t)$ representing the forces (longitudinal, transverse, and vertical) and moments (relative to the longitudinal axis of the flexible track beam) exerted by the tire on the beam; $F_{X_f}(t)$、$F_{Y_f}(t)$、$F_{Z_f}(t)$、$M_{X_f}(t)$are the support forces of the track beam.

In addition, the damping matrix of the track beam is calculated by the following formula:

$$C_b = \frac{2\xi_b}{\omega_b} K_b \tag{8}$$

In the formula: $\xi$is the damping ratio; $\omega$is a pinned vibration mode; K is the stiffness matrix.

In summary, by combining them, the motion equation of the flexible track beam can be obtained as follows:

$$M_b \ddot{q}_b + C_b \dot{q}_b + K_b q_b = F_b \tag{9}$$

In the formula, M_b、C_b、K_b is the mass, damping, and stiffness matrix of the flexible track beam; q_b、$\dot{q}_b$、$\ddot{q}_b$ is the displacement, velocity, and acceleration matrices for the flexible track beam system; F_b is the load vector acting on the flexible track beam.

2.4 Coupled dynamics model

Based on equations (11) and (19) above, the vehicle system, flexible track beam dynamics, and wheel rail contact relationship constructed earlier are combined to construct the dynamic motion equation system of the train flexible track beam coupling system, which takes the following form.

$$M_{vb} \ddot{q}_{vb} + C_{vb} \dot{q}_{vb} + K_{vb} q_{vb} = F_{vb} \tag{10}$$

3 Research on comfort of straddle type monorail-flexible track beam coupling system

3.1 Construction of comfort evaluation indicators

Based on previous references, it can be found that comfort is also a common evaluation index for assessing the comfort and smoothness of the formation vehicle system, which comprehensively reflects the degree of influence of the vibration of the formation vehicle system on passenger riding comfort. In this section, when evaluating the comfort of the coupling system between the straddle type monorail and the flexible track beam, Sperling stability indicators were used for evaluation.

3.2 Study on the impact of irregular track on comfort

In order to research the influence of track roughness on the comfort of the straddle type monorail train-flexible track beam system, the surface roughness of the running wheels was simulated using the AAR6 spectrum and the Japanese measured monorail spectrum. In this section, only the amplification factor of the roughness amplitude was changed with in the range of 0～2.0 times. The calculation parameters of the flexible track beam were selected from the Z206-25 beam parameters of the typical section of the Chongqing dynamic load test, with a running speed of 40km/h and a three car train configuration[9-10]; Extract the dynamic response indicators of the head car MCF, and the dynamic response changes of the track beam system under different track irregularities and their amplitude multiples are shown in Figure 1.

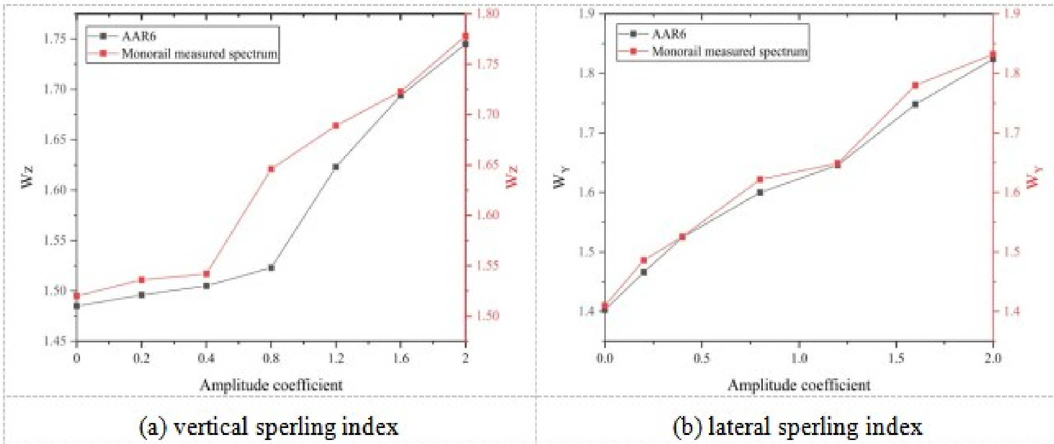


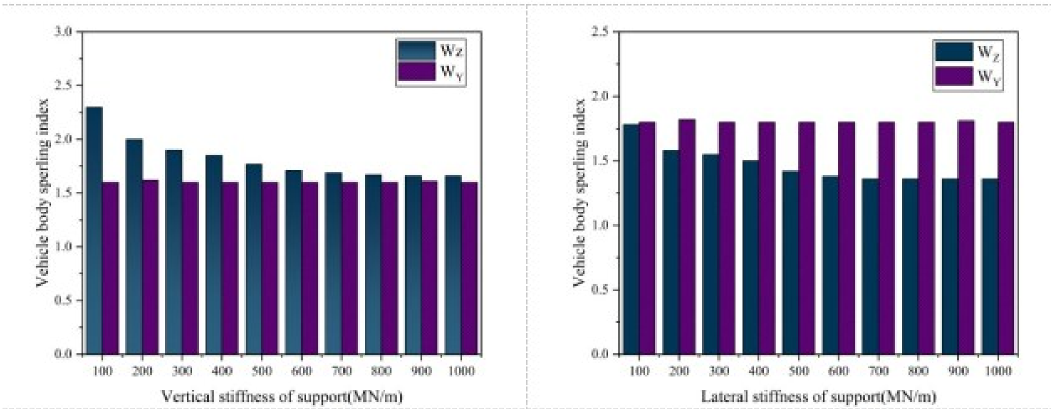
Figure 1 Comfort evaluation of Sperling index

From Figure 1, it can be observed that the here is a significant difference in the dynamic response amplitude of the vehicle system under two types of random track irregularities. The sperling index of the vehicle system using the American level six spectrum for the running wheels is slightly lower than that of the vehicle system using the single track measured track spectrum. In addition, as the amplitude of the two types of track surface irregularities increases; With the increase of the multiple of the roughness amplitude, both the vertical and horizontal Sperling indicators show an increasing trend, but the difference in the smoothness of vehicle operation under the two types of track roughness is relatively small.

3.3 Study on the influence of support parameters on comfort

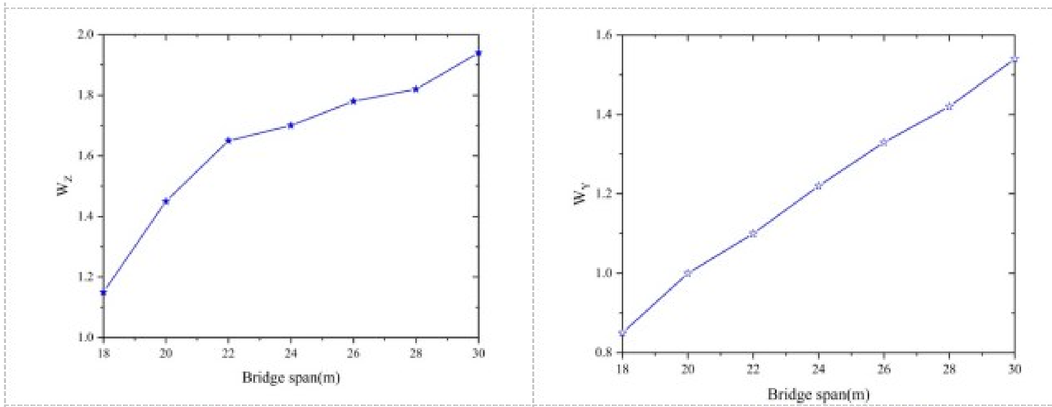
To investigate the influence of support parameters on the comfort of the vehicle system under the condition of meeting the vehicle load, references show that the vertical passenger comfort of the vehicle body is mainly affected by the vertical stiffness of the support, while the lateral stiffness only affects the lateral passenger comfort of the vehicle; And the dynamic response of the vehicle is most obvious when the grouped train travels at 60km/h on a 22m simply supported linear flexible track beam. This section takes this working condition as the research condition, using a three car train, with the vertical/lateral stiffness of the support varying within the range of 100MN/m to 1000MN/m. The vibration response of the MCF of the lead car is extracted, and the comfort response of the vehicle system is obtained as shown in Fig 2-3.

From Figures 2-3 , it can be seen that under the influence of the vertical stiffness of the support, as the vertical stiffness of the support increases, the Sperling index of the vehicle body decreases. When the vertical stiffness of the support is less than 400MN/m, it has a significant impact on the vertical stability of the vehicle body; The Sperling index of the vehicle body is almost unaffected by the vertical stiffness of the support. On the contrary, the lateral stiffness of the support has a significant impact on the Sperling index of the vehicle body. As the stiffness of the support increases, the lateral vibration response sharply decreases. When the lateral stiffness of the support exceeds 500MN/m, the decrease slows down and tends to stabilize. In addition, when the bridge span L<30, the vertical and lateral acceleration of the vehicle body and Sperling index increase to varying degrees with the increase of the bridge span, among which the vertical vibration response changes the most.



(a) Vertical stiffness of support (b) Lateral stiffness of support

Figure 2 The influence of support stiffness on Sperling index



(a) Vertical Sperling index (b) Lateral Sperling index

Figure 3 The influence of bridge span on Sperling index

4 Conclusion

Based on the coupling dynamic model of the straddle type monorail and flexible track beam constructed in this paper, the ride comfort of the straddle type monorail flexible track beam coupling system was studied as follows. Main research findings:

(1) There is a significant difference in the dynamic response amplitude of the vehicle system under two types of random track irregularities. The Sperling index of the vehicle system using the American Level 6 spectrum for the running wheels is slightly lower than that of the vehicle system using the single track measured track spectrum. In addition, as the amplitude of the two types of track surface irregularities increases, both the vertical and horizontal Sperling indicators show an increasing trend, but the difference in vehicle running stability under the two types of track irregularities is relatively small.

(2) Affected by the vertical stiffness of the support, as the vertical stiffness of the support increases, the Sperling index of the vehicle body decreases. When the vertical stiffness of the support is less than 400MN/m, it has a significant impact on the vertical stability of the vehicle body; The Sperling index of the vehicle body is almost unaffected by the vertical stiffness of the support. On the contrary, the lateral stiffness of the support has a significant impact on the Sperling index of the vehicle body. As the stiffness of the support increases, the lateral vibration response sharply

decreases. When the lateral stiffness of the support exceeds 500MN/m, the decrease slows down and tends to stabilize. In addition, when the bridge span L<30, the vertical and lateral acceleration of the vehicle body and Sperling index increase to varying degrees with the increase of the bridge span, among which the vertical vibration response changes the most.

About the Author

Huping Lu, Master's degree holder, School of Mechanical and Electrical Engineering, GANSU FORESTRY VOCTECH UNIVERSITY, Lecturer, Research Direction: Vibration and Noise Control of Rail Transit; Kaikai Song, Master's degree holder, School of Mechanical and Electrical Engineering, GANSU FORESTRY VOCTECH UNIVERSITY, Lecturer, Research Direction: Automotive Electronic Control Technology; Wangjian Che, Master's degree holder, School of Mechanical and Electrical Engineering, GANSU FORESTRY VOCTECH UNIVERSITY, Assistant, Research Direction: UAV Dynamics Model and Control System Design

References

[1] He, Xihe. Application and Prospect of Straddle Monorail Transit System in China[J]. Urban Rail Transit, 2015, 1(1): 26-34.

[2] Du Z, Wen X, Zhao D, et al. Numerical Analysis of Partial Abrasion of the Straddle-type Monorail Vehicle running Tyre [J]. Transactions of FAMENA, 2017, 41(1):99-112.

[3] Zhen, Yang, Du Z, et al. Research on the Influence of Straddle-Type Monorail Pantograph Head Parameter on Power Collection Quality[J]. Urban Rail Transit, 2017, 3(3):149–157.

[4] Zhou J, Du Z, Liao Y, et al. An optimization design of vehicle axle system based on multiobjective cooperative optimization algorithm[J]. Journal of the Chinese Institute of Engineers, 2018, 41(8):635-642.

[5] Goda K, Nishigaito T, Hiraishi M , et al. A curving simulation for a monorail car[C]// Railroad Conference. IEEE, 2002.

[6] Naeimi, Meysam, Tatari, et al. Dynamics of the Monorail Train Subjected to the Braking on a Straight Guideway Bridge[J]. Archive of Mechanical Engineering, 2015, 62(3):363-376.

[7] Knothe K, Grassie S L. Modelling of Railway Track and Vehicle/Track Interaction at High Frequencies[J]. Vehicle System Dynamics, 1993, 22(3):209-262.

[8] Mazilu T. Green's functions for analysis of dynamic response of wheel/rail to vertical excitation[J]. Journal of Sound & Vibration, 2007, 306(1-2):31-58.

[9] Lee C H, Kawatani M, Kim C W, et al. Dynamic response of a monorail steel bridge under a moving train[J]. Journal of Sound & Vibration, 2006, 294(3):562-579.

[10] Kim C W, Kawatani M. Effect of train dynamics on seismic response of steel monorail bridges under moderate ground motion[J]. Earthquake Engineering & Structural Dynamics, 2010, 35(10):1225-1245.