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ORIGINAL RESEARCH PAPERS

Dynamic Analysis of Suspension-Type Monorail Long-Span Cable-Stayed Bridge in a Wind-Vehicle-Bridge System

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Abstract The suspension-type monorail (STM) is a new type of rail transit, currently developing rapidly in China. Due to its short construction duration and high terrain adaptability, STM can save large land resources. In particular, by supplementing the traffic systems in large and medium-sized cities, STM can contribute to green tourism projects. However, no systematic study is devoted to the STM transit system in China, and there is still a lack of relevant knowledge and exploration, especially for the special combination system monorail bridge. In view of the real STM bridge, namely a long-span (55 + 100 + 55)-m cable-stayed bridge in this paper, and by applying wind-vehicle-bridge coupling vibration theory, ANSYS finite element method software, and Universal Mechanism multi-body dynamics software, finite element models are established for the bridge and multi-body vehicle, respectively. Furthermore, a co-simulation method is adopted to analyze vehicle-bridge coupling vibrations and ride comfort quality. According to the results, the dynamic responses of the monorail bridge and vehicle are greatly affected by the variation in wind speed, and it is necessary to take measures to decrease system vibrations, thereby ensuring ride comfort quality for vehicle passengers.

Keywords Suspension-type monorail · Cable-stayed bridge · Wind-vehicle-bridge coupling system · Ride comfort quality · Multi-body dynamics

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1 Introduction

With the rapid development of global urbanization, a growing number of people are migrating from the countryside to central cities, especially people in emerging developing countries. However, due to the rapidly growing population, great pressure is exerted on urban traffic systems, gradually creating a bottleneck and hindering development of urban construction, especially for the large and medium-sized cities in newly developing countries [1, 2]. Hence, a new type of rail transit system, called suspension-type monorail (STM), has emerged and attracted people's attention [3–6]. In 1901, the first STM system was established in Wuppertal, a city in western Germany. Since then, STM has operated normally for over 100 years [7]. In the 1950s, the Japanese imported and developed their STM technology, and there are four STM lines in operation currently [8]. In the 1990s, the world's largest developing country, China, also began its study of STM technology and made STM an alternative for solving traffic congestion problems of future cities. Also, several STM lines, including new energy projects and bases, have been established in China since the 2010s [9]. Considering the excellent terrain adaptability, STM transportation systems contribute to saving of construction costs and urban land resources. Moreover, as a typical lightweight urban transportation form, STM could be used as a supplement to the existing public transportation system. Particularly, STM is suitable for passenger transportation connection lines and sightseeing tourism projects. Hence, STM has broad development space and application prospects in modern large and medium-sized cities [10]. Furthermore, the STM is usually composed of monorail bridge beams and pier structures. Generally, the monorail bridge beam adopts a semi-enclosed box-girder structural design, with the bottom used as the STM vehicle running track. Also, both STM structures could be fabricated with steel in the processing plant. To date, many researchers and scholars [11] have explored STM, including monorail vehicle and bridge beam structure design.

Jun et al. [12] introduced the development and global application trend of STM and indicated that STM is a very promising transit mode for its evident advantages in design and route selection. Many countries have launched the study and application of STM, including the United States, Japan, Australia, Russia, Brazil, and China,. Mohammad et al. [13] explored the structural design of a monorail bridge pile with soil–pile interaction considered, and used a simplified calculation method to simulate monorail bridge vertical vibration in different soils. Jiang et al. [14] analyzed the STM vehicle-bridge coupling system by adopting a finite element model and multi-body dynamics method, and provided reasonable monorail vehicle design suggestions such as vehicle stiffener span increase to alleviate the resonance of the bridge-vehicle system. Bao et al. [15] created a bridge-vehicle coupling vibration model based on a simply supported beam laboratory line, thereby evaluating the safety and reliability of the STM transit system. They finally discovered that track irregularity is a critical factor for STM vibration safety, especially the A-level track irregularity that has a negative impact on system vibration safety. Naeimi et al. [16] assessed the dynamic response characteristics of a monorail bridge system, considering the specific bridge span and reflecting the dynamic forces and reactions of the bridge structure caused by vehicle movement. Lv et al. [17] tested vertical acceleration of STM on the first Chinese laboratory line, and pointed out that the vertical acceleration would increase considerably due to wheel eccentricity, and that the vertical vibration of STM caused by wheel eccentricity could be reduced by decreasing the secondary stiffness. Bao et al. [18] investigated the aerodynamic performance and vibration characteristics of 30 m-span simply supported beam monorail bridge in a wind-vehicle-bridge coupling system by conducting numerical simulation and laboratory tests during a meeting of two monorail vehicles, and indicated that the fluctuating wind has an obvious impact on the lateral responses of monorail vehicles and the running safety of the STM. Cai et al. [19] established a simply supported beam vehicle-bridge coupling system and analyzed the dynamic response characteristics of the coupling system. According to the comparison between numerical simulation results and field test data, better agreement can be achieved by considering the bridge as a flexible structure instead of a rigid body, and the numerical simulation method can accurately reflect the vehicle-bridge dynamic response. Xu et al. [20] explored the key problems of vertical vibration and proposed a dynamic model based on tire vertical equivalent stiffness. Wang et al. [21] compiled a program with Visual Basic (VB) language in order to solve the motion-governing equation of the monorail vehicle-bridge coupling system.

As illustrated by those references and studies, there are already some systematic and mature studies on the STM transport system. Most of the studies focus on monorail vehicle parameters design, track irregularity, vehicle-bridge system dynamic responses, or simply supported beam monorail structure design. However, there is a lack of relevant studies and references on special STM bridge structure designs, such as cable-stayed bridges, arch bridges, and continuous rigid frame bridges. The study on vehicle-bridge dynamic responses of STM transportation system is limited to the simply supported beam structures.

As a new type of urban traffic structure, suspended rail transit has gradually been accepted by major cities, with an increasing number of relevant studies. However, the studies are largely limited to the simply supported rail beams, and there are no sufficient studies on vehicle-bridge coupling of long-span structures. Due to the suspension characteristics, suspended rail transit is more susceptible to the influence of cross-wind load, so the availability of relevant studies is critical.

To analyze vehicle-bridge dynamic response characteristics of the STM, a multi-body dynamic simulation model is established with track irregularity and fluctuating wind effect considered, thus assessing the dynamic responses of a wind-vehicle-bridge coupling system. The dynamic response characteristics of the coupling system include the vibration acceleration of vehicle and bridge, as well as the vertical and lateral displacements of the bridge when vehicles pass through the bridge. Moreover, the ride quality of the STM at different velocities is also studied, thereby providing a suggestion for the operating management of STM. Hence, the results presented in this paper could provide relevant information for future cable-stayed monorail bridge construction programs.

2 Wind-Vehicle-Bridge Coupling System

2.1 Bridge System

To analyze the STM cable-stay bridge vibration frequency, a finite element model is established for the bridge with ANSYS software. In this finite element model, bridge structures such as pylon, bridge pier, and bearing cap adopt the BEAM 188 unit, the monorail bridge beam adopts the SHELL63 unit, and the bridge cable adopts the LINK10 unit. The STM cable-stayed bridge finite element model consists of 89,063 nodes and 10,896 cells, as shown in Fig. 1.

The STM cable-stayed bridge motion equation can be described as follows:

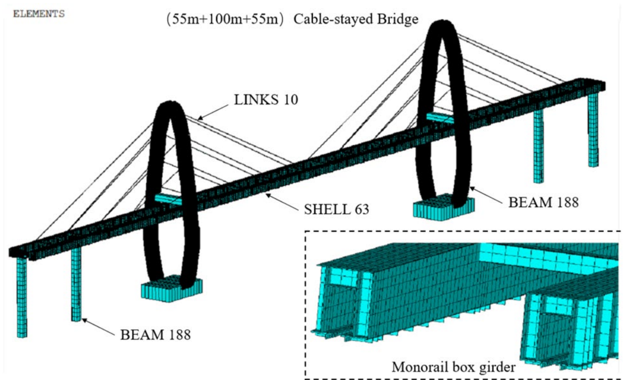

Fig. 1 STM cable-stayed bridge finite element model

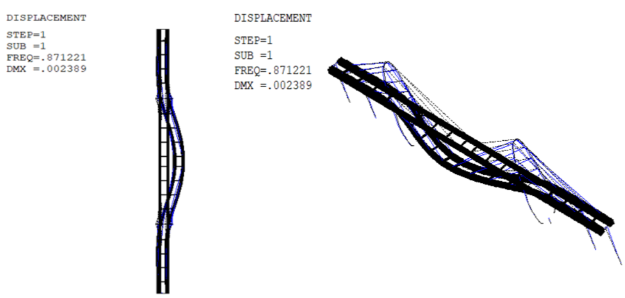

Fig. 2 The first-order frequency and vibration mode of STM bridge

$$m\ddot{v}(t) + c\dot{v}(t) + kv(t) = p(t) \quad (1)$$

where m, c, and k refer to the mass, damping, and stiffness of bridge, respectively; $\ddot{v}(t)$, $\dot{v}(t)$, and $v(t)$ represent the displacement, velocity, and acceleration vectors of the bridge, respectively; and $p(t)$ is the load imposed on the bridge, including wheel-rail force and wind force during the interaction of a vehicle with the bridge.

According to the analysis of natural vibration characteristics, the first-order fundamental frequency and vibration mode of an STM bridge structure are shown in Fig. 2. The first-order formation of the track beam is transverse bending, caused by the small section of the track beam and the weak transverse stiffness. The first-order vertical bending frequency of the track beam is 1.2, which can affect the vertical deformation of the track beam.

2.2 STM System

STM is quite different from normal railway trains. In this program, a single monorail vehicle consists of two carriages, with each having a length of 11.0 m and a width of 2.5 m. As for the monorail vehicle, the maximal running speed is 80 km/h, and the designed operating speed is 60 km/h.

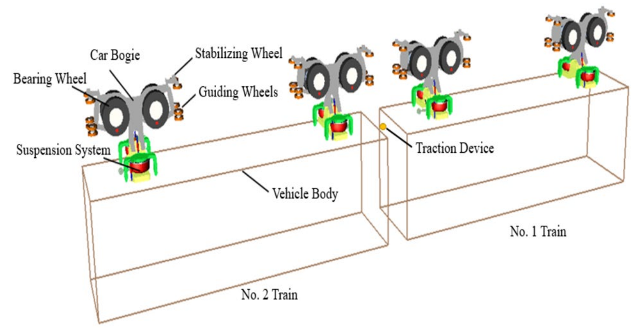

Fig. 3 Monorail vehicle dynamics model

Table 1 Degrees of freedom of STM monorail vehicle

Vehicle part name	Lateral	Vertical	Rolling	Yawing	Pitching
Vehicle body	Y_c	Z_c	φ_c	ψ_c	θ_c
Bogie ($i=1,2$)	T_{ti}	Z_{yi}	φ_{ti}	ψ_{ti}	θ_{ti}
Suspension frame ($i=1,2$)	–	–	–	ψ_{di}	–
Guiding wheel ($i=1$~8)	–	–	–	θ_{zi}	–
Bearing wheel ($i=1$~4)	–	–	–	–	θ_{zi}
Center pin ($i=1,2$)	–	–	ψ_{si}	–	–

To analyze the dynamic responses of the vehicle when running through the bridge, a monorail vehicle model is created by applying Universal Mechanism multi-body dynamic calculation software. The monorail vehicle model is composed of vehicle bodies, bogies, wheel-sets, traction devices, and suspension systems, and the vehicle dynamics model is shown in Fig. 3.

When building the monorail model, some necessary simplifications are made to accurately simulate the vehicle. For example, the rigid structure of the model merely considers its weight, and the shape is replaced by similar regular geometric figures, such as car body and frame. The running wheel and steering wheel of the bogie are both rubber wheels, similar to the automobile tire, and the modeling is based on the Fiala automobile tire model. The connection parts of the monorail vehicle model are simulated by the spring and damping system.

Some simplifications are made as for the monorail vehicle dynamics model. Hence, each monorail train body and bogie have five degrees of freedom (DOFs), namely vertical displacement Z, lateral displacement Y, roll displacement R_x, yaw displacement R_z, and pitch displacement R_y.

The DOFs of other train structures include suspension frames, center pins, and wheel-sets. There are 31 DOFs in this STM model for one train. Moreover, the DOF of the monorail vehicle model structure is exhibited in Table 1.

2.3 Wind Effects of STM

Wind load is a random excitation in the environment. With the increase in train speed, aerodynamic problems have become crucial for train speed, so it could be a decisive factor affecting operating safety of the vehicle [22]. Although the STM runs at a lower speed than a high-speed train, the wind load factor needs to be considered to provide better suggestions for monorail vehicle operation.

2.3.1 Mean Wind Effect

The mean wind load is determined by the mean wind flow and static aerodynamic coefficients. When the mean wind load is applied to the structuring and running vehicle of monorail bridge, the mean wind load may cause lateral and vertical displacements of the entire bridge structure, thereby affecting the running safety of monorail vehicles.

The mean wind acting on monorail bridge and vehicle could be deemed as a drag force, a lift force, and a moment, with the formula described as follows:

$$F_L = \frac{1}{2}\rho U^2 C_L B \tag{2}$$

$$F_D = \frac{1}{2}\rho U^2 C_d H \tag{3}$$

$$F_m = \frac{1}{2}\rho U^2 C_y B^2 \tag{4}$$

where ρ is the density of air; U refers to the mean wind speed; B and H represent the width and height of the bridge box-girder structure or monorail vehicle; and F_L, F_D, and F_m are the lift coefficient, drag coefficient, and moment coefficient, respectively. The three coefficients are exhibited in Fig. 4.

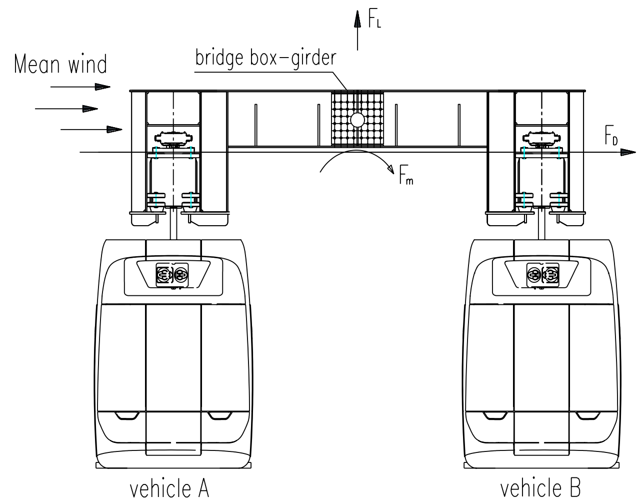

Fig. 4 Three coefficients of mean wind effect

2.3.2 Fluctuating Wind Effect

The buffeting of the bridge structure and monorail vehicle is induced by fluctuating wind, consisting of the along-wind part and the vertical part. According to previous research, the fluctuating wind field can be regarded as a stationary random process. Generally, two methods are used for simulating the fluctuating wind load effect, namely the regression method based on linear filtering technology and the spectral method based on trigonometric series superposition.

As discovered by comparing the two methods, the spectral method seems more reliable and reasonable and has been widely used in bridge construction engineering, despite the greater calculation required.

With regard to the fluctuating wind simulation of the STM system, the Kaimal–Simiu spectrum is selected based on the Chinese *Code for Design on Railway Bridge and Culvert*. The expression of the fluctuating wind spectrum can be described as follows:

$$\frac{nS_u(n)}{u_*^2} = \frac{200f}{(1+50f)^{\frac{5}{3}}} \tag{5}$$

where $S_u(n)$ refers to the lateral fluctuating wind spectral density function; n represents the pulsating frequency of the wind; f denotes similarity rate coordinates, also known as Mourning coordinates and $f = \frac{nz}{u(z)}$; and u_* is the frictional speed of airflow.

According to this method, the wind speed time history from the wind spectrum at any spatial position could be simulated by programming. As for the fluctuating wind field simulation in this STM system, the following items are determined, including limiting frequency $\omega_u = 5\,\pi$ rad/s, frequency point number $N = 1024$, and time step $\Delta t = 0.1$ s. The fluctuating wind time-history curve at different velocities of the STM system is shown in Fig. 5.

3 Wind-Vehicle-Bridge System

3.1 Coupling System Simulation

The dynamics analysis of the wind-vehicle-bridge coupling system can be described as follows. Firstly, an STM bridge FE model is created with coordinates of all bridge nodes, vibration modes, mass, and stiffness matrix information

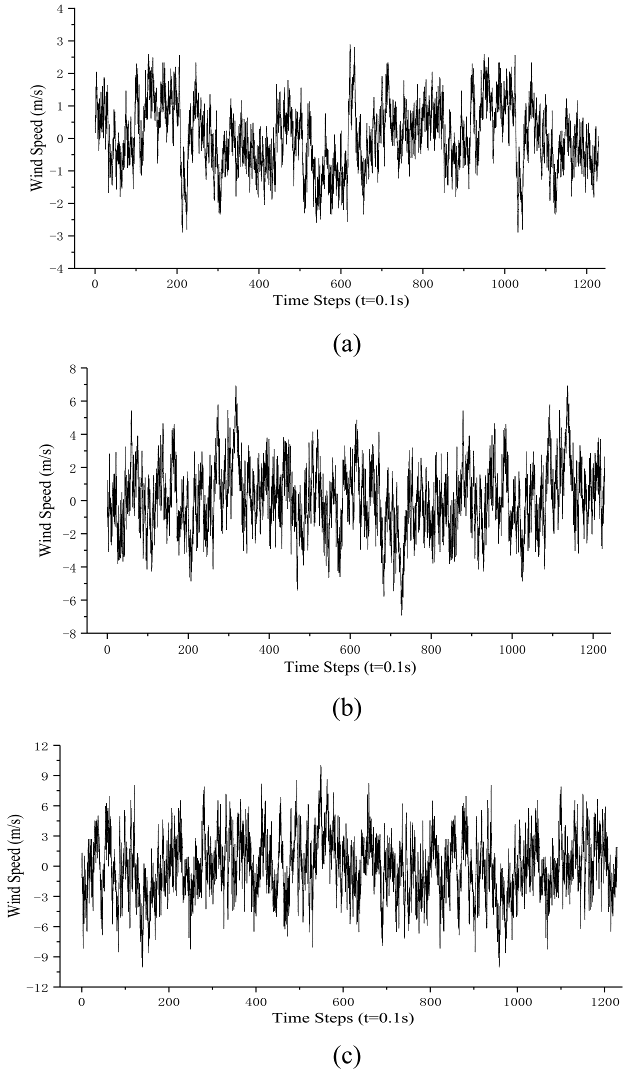

Fig. 5 Fluctuating wind time-history curve of STM. **a** speed =5 m/s; **b** speed =10 m/s; **c** speed =15 m/s

contained, and the model is transferred to a flexible structure body. Secondly, the monorail vehicle is established by adopting multi-body dynamics software Universal Mechanis. Finally, a force element is used in inputting aerodynamic parameters of the STM system, as well as aerodynamic load variation when the train is running on the bridge. The dynamic analysis of the coupling system is presented in Fig. 6.

3.2 Mean Wind Load

When a monorail vehicle passes through the bridge, the wind flow will be greatly affected by the shape of the STM system structure, including bridge box-girder and vehicle body. Variation in aerodynamic forces could affect the

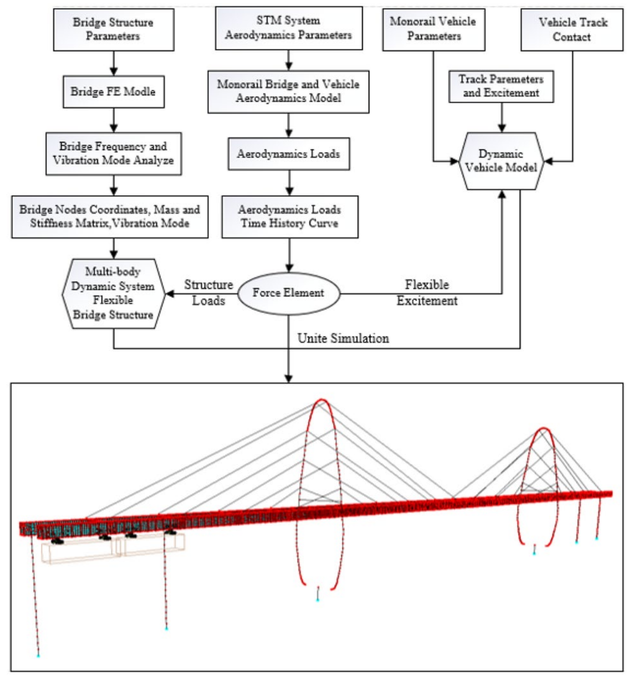

Fig. 6 Multi-body dynamic simulation process

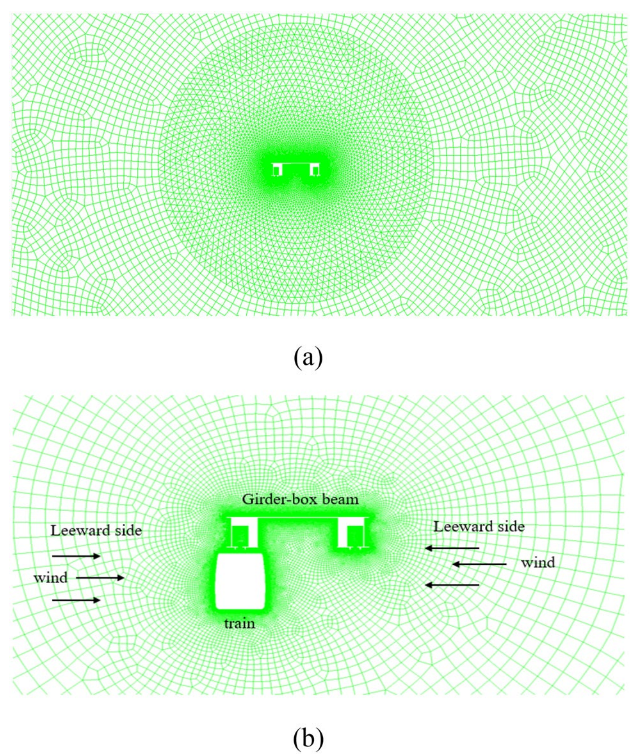

Fig. 7 CFD model of STM mesh schematic diagram. **a** box-girder; **b** box-girder and monorail

running safety of a monorail vehicle. To analyze the aerodynamic characteristics of wind flow for a monorail vehicle, the computational fluid dynamics (CFD) method is adopted.

As exhibited in Fig. 7, a two-dimensional (2D) numerical simulation of a uniform wind field is applied by employing a commercial CFD program, Fluent, to obtain the aerodynamic coefficients. The aerodynamic coefficients of the single beam and the beam with a vehicle are calculated.

A pressure-based solver is selected for transient flow for the setup of the shear stress transport (SST) k-ω model in Fluent. Pressure-velocity coupling is calculated by adopting the PISO (Pressure-Implicit with Splitting of Operators) scheme. Spatial discretization of pressure is solved using the PRESTO (PRESsure Staggered Option) scheme. The second-order upwind scheme is used to measure the spatial discretization of turbulent kinetic energy and specific dissipation rate. The time step calculated is 10^{-5} s. The boundary type of the girder and train is a no-slip stationary wall. The thickness of the first-layer grid cell is 0.01 mm, with $y+$ value less than 3. Cell thickness increases from the inside to the outside based on the geometric sequence, and the expansion rate of adjacent grid cells is 1.1. There are approximately 250,000 grids in total. In Table 2, the calculated aerodynamic coefficients of the suspended bridge and vehicle at different wind angles and directions are presented.

3.3 Track Irregularity

Track irregularity is an important factor that affects the running quality of monorail-suspended vehicles. Unlike conventional rail vehicles, track irregularity in monorail vehicles is mainly caused by factors such as box-girder manufacturing error, installation error, residual deformation of steel material, and uneven settlement of STM foundations during operation [23, 24]. To date, there have been many studies on track irregularity in traditional trains. Moreover, many developed countries including the United States, Germany, and Japan have already obtained their own track irregularity spectrums based on their own operating railway track data [25, 26]. However, most of the track irregularity spectrums aim at high-speed train tracks, and there is still no mature and systematic track irregularity spectrum regarding STM.

Hence, it is necessary to monitor the track irregularity data of STM systems in field tests. In addition, a track irregularity test study was previously performed on an STM system in a laboratory test line [27]. STM amplitudes of track irregularity for different wheels are exhibited in Fig. 8. According to the test data, the irregularity amplitudes of the driving track, guiding track, and stability track of the STM are about 3.0 mm, 1.5 mm, and 1.5 mm, respectively.

3.4 Flexible Bridge System

Considering the bridge structure of the STM vehicle-bridge coupling vibration dynamic system model, there are rigid and flexible bridges. According to previous research, a flexible bridge structure seems to be more reliable than a rigid one. Hence, a finite element suspended cable-stayed structure model with a length of 210 m is established. The FE model has all details of the bridge box-girder beam structure, except for the roughness of the inner side of the track beam. Thus, random manufacturing errors of the beam are not taken into consideration. The data exchange interface and contact relation of vehicle-bridge coupling system are implemented using ANSYS design parametric language (ADPL).

Table 2 Mean wind aerodynamic coefficients of bridge and vehicle

Name	Angle (°)	Lift coefficients, F_L (windward/leeward side)		Drag coefficients, F_D (windward/leeward side)		Moment coefficients, C_m (windward/leeward side)	
Beam	−6	0.146	1.307	1.704	1.282	−0.073	0.066
Train		−0.128	0.204	1.423	1.035	0.077	−0.047
Beam	−4	0.106	1.243	1.846	1.505	−0.080	0.063
Train		−0.179	0.154	1.537	1.109	0.079	−0.038
Beam	−2	0.064	1.259	1.895	1.801	−0.088	0.061
Train		−0.252	0.079	1.570	1.221	0.076	−0.020
Beam	0	−0.006	1.151	1.812	2.095	−0.085	0.069
Train		−0.329	0.069	1.502	1.259	0.063	−0.011
Beam	2	−0.040	1.171	1.947	2.329	−0.094	0.075
Train		−0.431	0.033	1.623	1.333	0.065	0.004
Beam	4	−0.085	1.211	1.843	2.568	−0.093	0.074
Train		−0.484	−0.011	1.572	1.311	0.053	0.012
Beam	6	−0.130	1.271	1.767	2.670	−0.091	0.089
Train		−0.544	−0.297	1.534	1.541	0.044	0.046

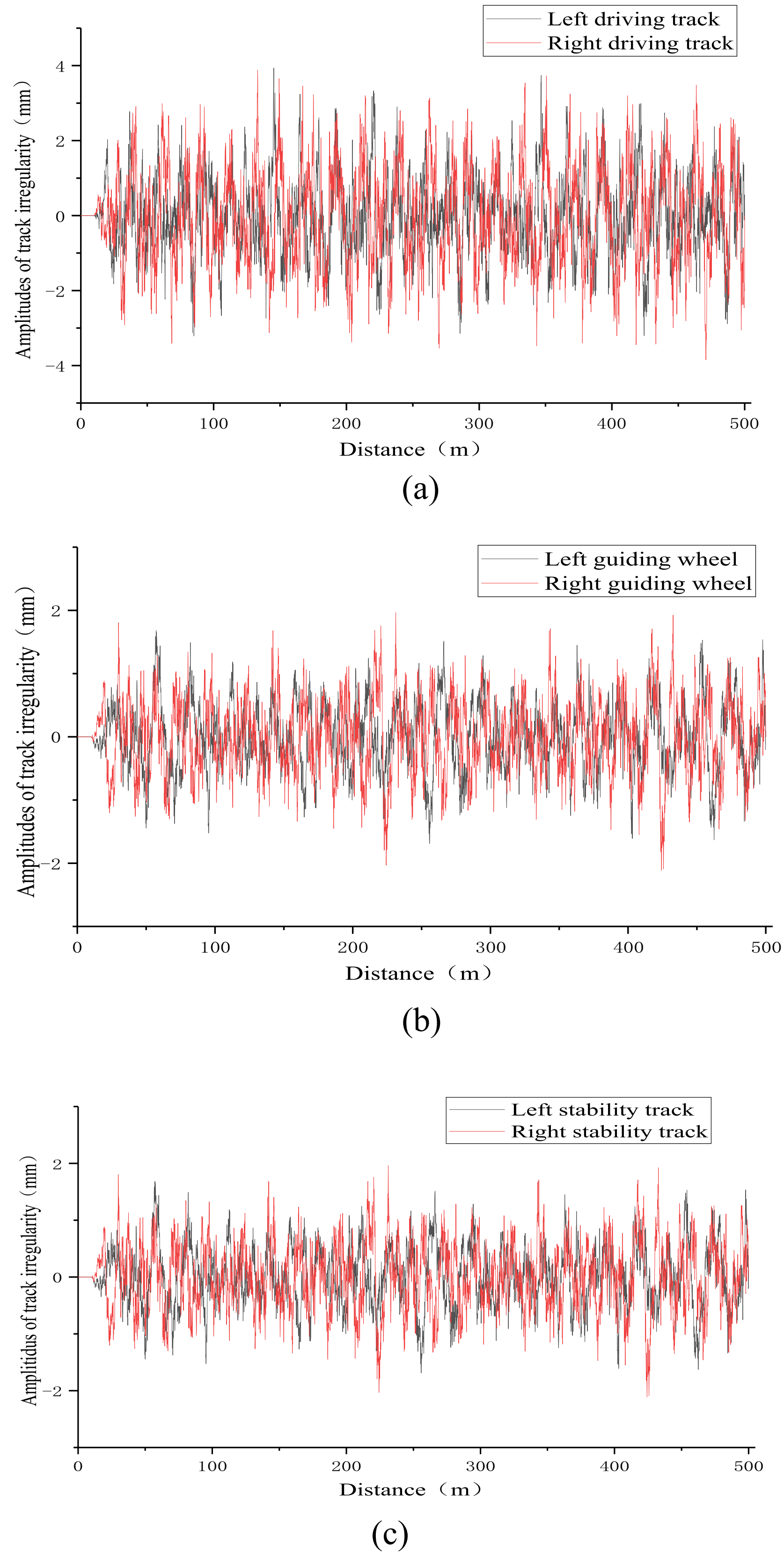

Fig. 8 Field test data of STM track irregularity. **a** driving wheels; **b** guiding wheels; **c** stability wheels

Based on this, the dynamic responses of coupling wind-vehicle-bridge system are simulated. By comparing the analyzed data of monorail vehicles and bridge structures, some useful conclusions are drawn, thereby providing practical and safety suggestions and guidance for the future STM system operation management.

4 Dynamic Analysis of STM Coupling System

4.1 Dynamic Response of Monorail Vehicle

In the STM system, dynamic responses of vehicle are expressed by vehicle acceleration and Sperling coefficient when a monorail vehicle is crossing through the bridge.

4.1.1 Vehicle Acceleration

According to the monorail design plan, vehicle velocity is 60 km/h in operating condition. This suggests that it will take the vehicle 12.57 s to cross through the STM cable-stayed bridge. According to the detailed data on vehicle acceleration analysis, time step is taken as 0.005 s. Acceleration variations of the STM No. 1 train at different wind speeds are exhibited in Fig. 9.

As observed, wind speed has a great impact on monorail vehicles. The peak acceleration of STM occurs around time step = 1100. The results of vehicle acceleration are segmented appropriately, with 2 s taken as an interval. As indicated by the results, root mean square value of acceleration reaches the maximum in the range of 1000–1200 time steps, and this is consistent with the condition when a vehicle is driving in the span of bridge. At the four wind speeds, the root mean square values of the lateral acceleration of No. 1 STM are 0.346296, 0.316788, 0.396164, and 0.635093,

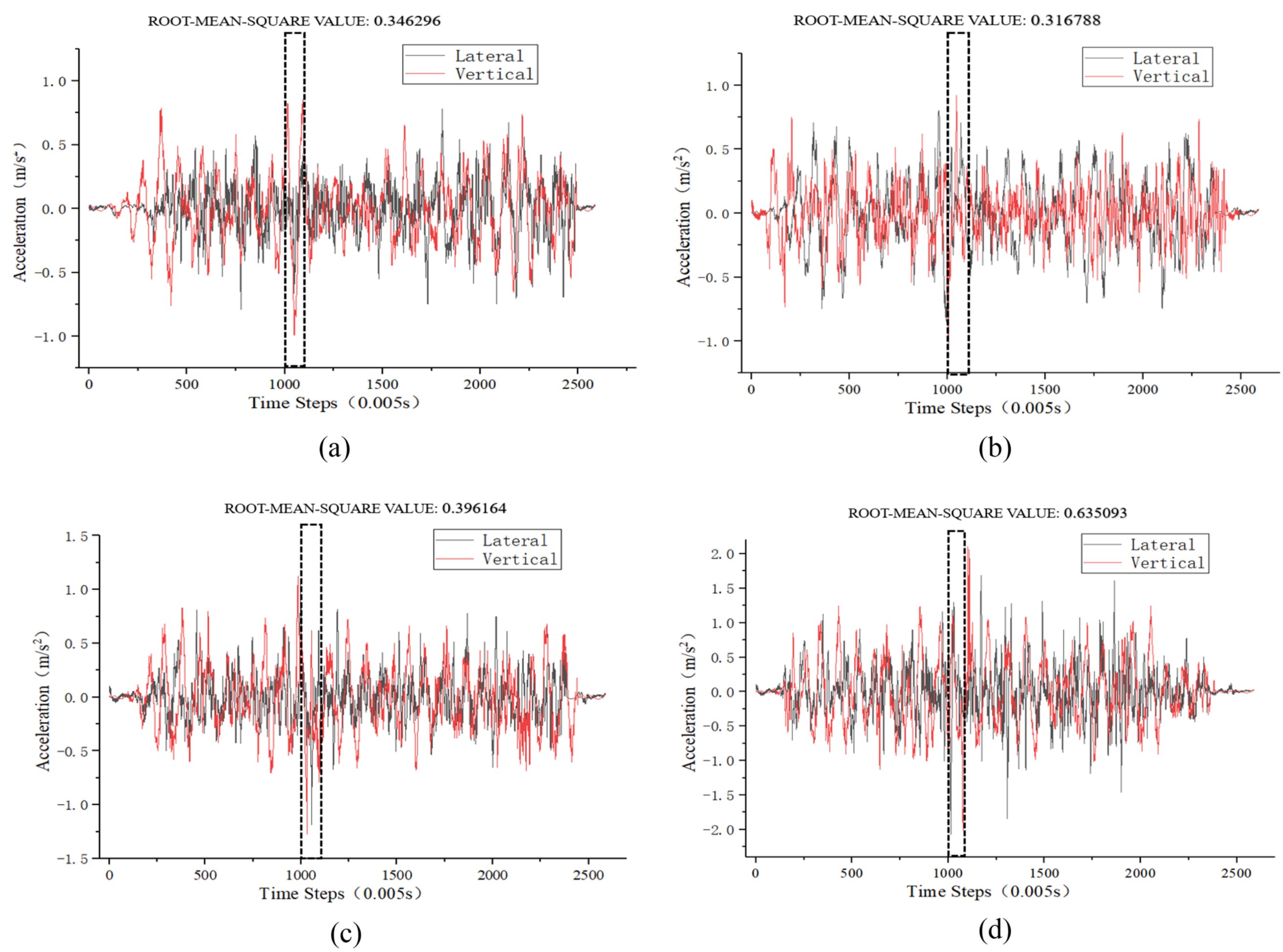

Fig. 9 Monorail vehicle acceleration under different wind speed. **a** wind speed = 0 m/s; **b** wind speed = 5 m/s; **c** wind speed = 10 m/s; **d** wind speed = 15 m/s

respectively. This indicates that the speed variation of fluctuating wind has a remarkable impact on STM. Dynamic responses of monorail vehicle will change greatly at different wind speeds, leading to a decrease in vehicle running quality and causing negative effects on ride comfort quality of passengers. Hence, it is necessary to take vehicle running quality into consideration.

4.1.2 Vehicle Running Quality

The designed speed of the STM is 60 km/h during normal operation. Moreover, considering a further increase in passenger and acceleration requirements, the maximal speed of monorail vehicle is 80 km/h. Hence, the dynamic response simulation speed range of 60–80 km/h is selected for the coupling system, and monorail vehicle ride quality data is provided for the further acceleration requirement.

The Sperling coefficient is an important coefficient used in evaluating vehicle running quality, and can be expressed as follows:

$$W = 3.57 \sqrt[10]{\frac{A^3}{f} F(f)} \tag{6}$$

where A is monorail vehicle vibration acceleration; f denotes vibration frequency; and $F(f)$ refers to the correction factor associated with vehicle vibration.

The Sperling coefficient calculation process is created and programmed by applying MATLAB mathematical software, with the results exhibited in Table 3.

As observed, STM has excellent ride quality. Especially in a windless environment, the vehicle ride quality is only affected by the vehicle running speed when increasing from 60 to 80 km/h. However, when the wind speed is under 5 m/s, the Sperling coefficient of monorail vehicle is less than 2.5, indicating that the STM transit system is reasonable and reliable in structural design and meets the normal operating requirement. Under a normal running situation, the vehicle passengers may not feel uncomfortable when considering vehicle body vibration or aerodynamic load variation induced by the wind.

With the increase in wind speed, the variation of aerodynamic loads will be harmful to vehicle ride quality. The Sperling coefficient of a vehicle under normal operating velocity = 60 km/h is over 2.75 at the wind speed exceeding 10 m/s and over 3.0 at the wind speed of 15 m/s. As illustrated by the results, the increasing wind speed is a critical factor affecting the ride experience of vehicle passengers. When the wind speed approaches 10 m/s, vehicle passengers would be able to feel the vibration caused by wind aerodynamic load variation but it would still be tolerable. Nevertheless, in some extreme situations, if the wind speed is over 15 m/s, passengers will feel extremely uncomfortable due to the body vibrations of the vehicle. Hence, considering the safety and health of the passengers, some limited measures should be taken.

4.2 Bridge Dynamic Response

Dynamic responses of the STM system cable-stayed bridge structure include displacement and acceleration when the vehicle is crossing through the bridge. In this case, the vehicle running velocity is 60 km/h, and a point at the mid-span is chosen as a marked point to reflect the dynamic responses of the bridge structure. The calculated results of bridge displacement and acceleration are presented in Figs. 10 and 11.

As shown in Fig. 10a, wind speed has a negative impact on the lateral displacement of the bridge. The mid-span peak values of lateral displacement of STM bridge under different velocities occur when the vehicle is crossing through the bridge. With the increase in mean wind speed, the lateral displacement of the bridge shows obvious changes. The lateral displacement of the mid-span marked point increases from 2.04 to 7.16 mm along with the increase in mean wind speed from 0 to 15 m/s. However, vertical displacement of monorail-suspended bridge is more stable compared with lateral displacement of the bridge. Fig. 10b indicates the vertical displacements of the bridge under different wind speeds. It can be found that the wind speed variation slightly affects the vertical displacement of the STM bridge, and the maximal value of vertical displacement occurs when the vehicle is crossing through the mid-span marked point. This phenomenon is greatly related to the calculated mass of the monorail vehicle.

Fig. 11 shows a time history curve of acceleration of the STM system bridge. As observed, the peak value of bridge

Table 3 Monorail vehicle Sperling coefficients in different conditions

Wind speed (m/s)		0			5			10			15		
Vehicle speed (km/h)		60	70	80	60	70	80	60	70	80	60	70	80
Sperling No. 1 train	Lateral	2.019	2.108	2.089	2.139	2.308	2.421	2.491	2.671	2.768	2.812	2.916	3.094
	Vertical	2.353	2.318	2.382	2.398	2.408	2.468	2.588	2.782	2.791	2.953	3.105	3.282
Sperling No. 2 train	Lateral	2.165	2.167	2.085	2.263	2.347	2.402	2.592	2.692	2.902	2.738	2.869	3.101
	Vertical	2.291	2.301	2.460	2.458	2.567	2.698	2.781	2.851	3.068	3.122	3.246	3.406

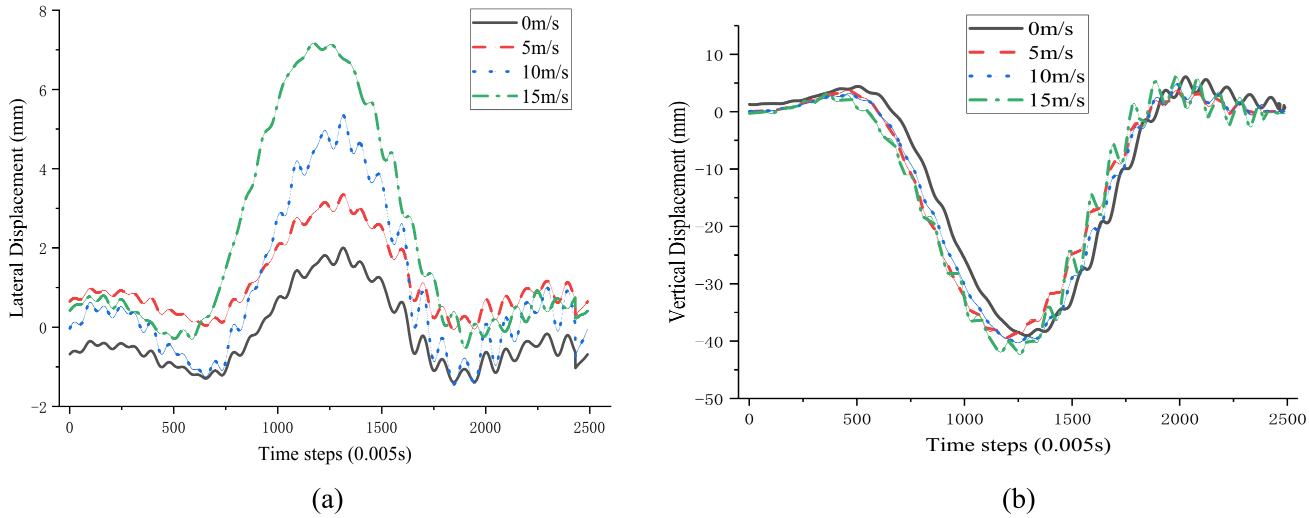

Fig. 10 Time histories of displacements. **a** lateral displacement; **b** vertical displacement

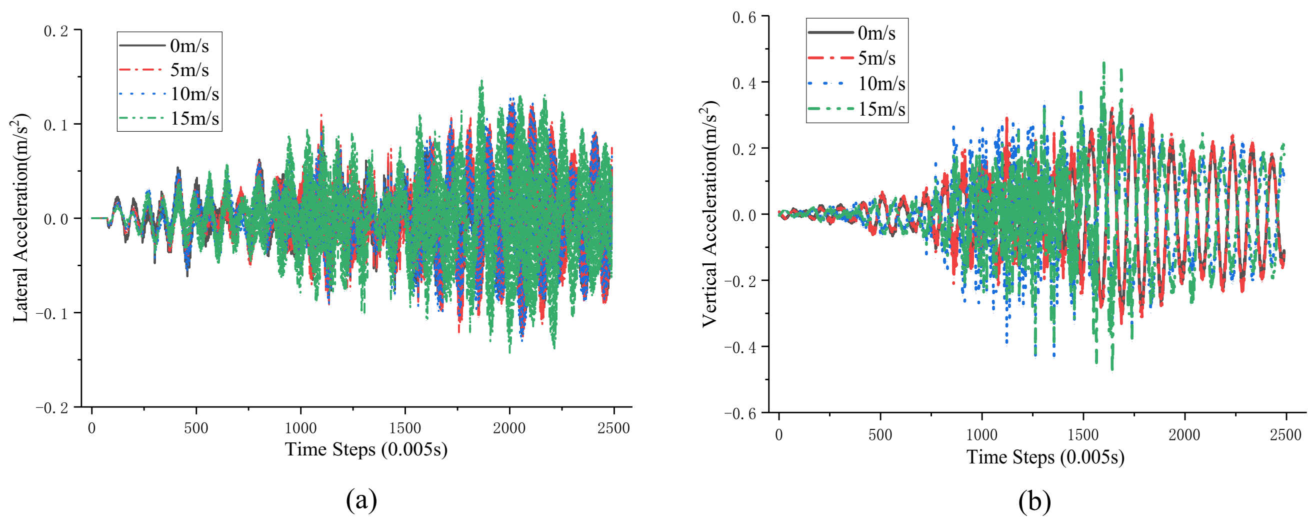

Fig. 11 STM bridge time history curves of accelerations. **a** lateral acceleration; **b** vertical acceleration

acceleration is affected by wind speed. With the increase in wind speed, the maximum lateral acceleration and vertical acceleration of the monorail bridge slowly increase from 0.102 m/s^2 to 0.149 m/s^2 and 0.304 m/s^2 to 0.467 m/s^2, respectively. Simultaneously, the calculated time history curve of acceleration changes in a highly consistent manner. This indicates that wind speed variation may not have an obvious impact on dynamic vibration performance of bridge structure, and it can magnify peak value of vibration of the bridge.

5 Conclusions

Based on the multi-body dynamic coupling method, the windmill coupling effect between the 31-DOF vehicle model and long-span rail girder bridge is realized in this paper, and a vehicle-bridge dynamic coupling model is established, thereby analyzing the dynamic responses of STM cable-stayed bridge and running safety of monorail vehicle at different velocities and wind speeds. Moreover, the possibility of large-span suspended rail transit is explored. Based on this study, some practical and useful conclusions and suggestions are drawn as follows:

1. According to the co-simulation results, the lateral dynamic responses of STM are more sensitive than the

vertical dynamic responses when the fluctuating wind speed increases. Those changes would have a negative impact on the ride comfort quality and safety of passengers.

2. When wind speed = 0 m/s, STM shows "excellent" running quality, and both lateral and vertical Sperling coefficients of the vehicle are lower than 2.5. This indicates that the STM system is reasonable in design. With the increase in wind speed, the running quality of the vehicle will change slightly, but such change may not lead to a decrease in quality. The running quality of the monorail vehicle will still remain at the "excellent" level when the wind speed remains at 5 m/s or below.
3. With the increasing wind speed, the vehicle running quality decreases from "excellent" to "good." When the wind speed reaches 15 m/s, the vehicle running quality decreases to "poor." The results indicate that the influence of transverse wind is the key factor for the running quality of vehicle-bridge coupling of long-span rail beams.
4. As demonstrated by the dynamic response data of the STM cable-stay bridge in this study, the design of the bridge structure is reasonable. When the vehicle running speed increases from 60 to 80 km/s, the bridge structure design plan not only may meet the present normal operating requirements but may possibly also allow future vehicle acceleration.

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Declarations

Conflict of interest The author(s) declare no potential conflicts of interest with respect to the research, authorship, and/or publication of this article.

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