

Transverse vibration characteristics and influence of passenger car window glass in high-speed train passing through tunnel

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Abstract

Purpose – This paper aims to analyze the transverse vibration characteristics of the high speed train window glass when passing through tunnel.

Design/methodology/approach – The lateral vibration acceleration response of glass chamber of high-speed train CR400BF-A on Beijing - Chengdu high-speed railway was tested at different speeds through the tunnel entrance, exit, tunnel interior, Tunnel Group and rendezvous time in the tunnel, the lateral distribution characteristics of vibration frequency and vibration power amplification coefficient of glass of high-speed train were analyzed.

Findings – The results show that: The vibration of the high-speed train glass increases significantly during the tunnel, and the amplitude of vibration acceleration in the tunnel is significantly higher than outside the tunnel as the travel speed increases; the amplitude of lateral vibration acceleration of the glass of a high-speed train does not vary with changes in tunnel length and is not affected by the aerodynamic effects of the tunnel when traveling inside the tunnel, but its vibrations create noticeable fluctuations during variations when encountering oncoming traffic; The vibration characteristics of the high-speed train glass are forced harmonic vibrations, the excitation frequency does not vary with travel speed and travel position changes inside and outside the tunnel. The lateral vibration acceleration of the glass of a high-speed train is applied vertically and uniformly to the glass surface as an “inertial force” and creates a cyclic bending vibration stress that can easily lead to fatigue damage.

Originality/value – The research results provide guidance for the prevention of glass failure in high-speed trains.

Keywords High-speed train glass, Crossing tunnel, Vibration acceleration amplitude, Vibration frequency, Dynamic amplification factor

Paper type Research article

1. Introduction

With its combined advantages of high speed, high capacity, efficiency, and low energy consumption, high-speed rail has become one of the essential components of passenger transportation in all countries. To ensure smooth traffic flow, the difficult mountainous areas of



high-speed rail lines often take the form of long tunnels and groups of tunnels through mountains or hills. (Guo, Zhao, & Yang, 2013) proposed that the operation of a high-speed train will result in significant vibration due to the interaction between the wheels and rails, the characteristics of the vehicle structure, and the combination of factors such as the acceleration and deceleration of the train, wind, and aerodynamics, which have typical parametric excitation and harmonic loading characteristics, and amplifies the reinforcements when passing through the tunnel. The dangers of high-speed train vibrations besides affecting traffic safety, these cyclic fatigue vibrations will cause dynamic stresses on the windows (high-speed train windows) of windshields and side windows of high-speed trains, undesirable phenomena such as dynamic fatigue and stress concentration (especially lateral vibrations perpendicular to the glass surface have more unfavorable impact on the use of the glass), resulting in the formation and propagation of cracks on the glass surface and inside, increasing the probability of glass shattering accidents.

At present, domestic and foreign research work on high-speed train body vibration problems mainly focuses on train multi-rigid body dynamics, rigid-flexible coupling dynamics, train operation safety under aerodynamic loads, vehicle-track coupling dynamics, and train vibration and noise reduction (Zhang, Chi, & Liu, 2007; Zhai, 2007; Wang, Zhai, & Cai, 2003; Wu, 2007; Guo, Zhao, & Yang, 2013). Netter (1998) combined multibody dynamics and finite element method to systematically study the fatigue damage of locomotive frames and proved that excessive dynamic stresses in the vehicle structure are the main cause of fatigue damage and fracture damage in the body structure. Carlbom (2001) used a combination of multibody dynamics and finite element methods to investigate the relationship between modal parameters and vibration characteristics of the vehicle body structure. Li, Miao, and Zhang (2016) studied the effects of different cross-sectional dimensions and different design parameters such as mass, material, structural strength, stiffness, and undercarriage equipment on the vibration characteristics of the car body based on the construction of a high-speed train body test stand. Liu, Zhang, and Xing (2018) showed that the vehicle vibration response in the frequency range of 0–50 Hz grows non-monotonically with the increase of train operating speed by establishing a rigid-flexible coupling dynamics model for trains. Wei, Boogaard, Núñez, Li, and Dollevoet (2018) and Aravanis, Sakellariou, and Fassois (2016) have directly installed sensors in different parts of the train to obtain the vibration status of the train in real time. Liu, Qiao, Zhao, and Zhuang (2018) used the integrated empirical modal decomposition (EEMD) method to decompose the train gearbox vibration acceleration signal and obtained the characteristic modal functions for high-speed trains. Zheng, Zhong, Chai, Chen, and Peng (2018) and Qian, Liang, and Gao (2015) developed a vehicle vibration acceleration prediction model using a neural network algorithm. There is no research on the effect of high-speed train running vibration on the window glass, and the existing results mainly focus on the effect of aerodynamic pressure, among which Shi (2002) and Jing, Liu, and Ren (2019) conducted the analysis of the stress variation of the train window glass with time and transient response of the car body and side windows based on ANSYS/DYNA software under the effect of high-speed train intersection pressure wave. Tian, Yao, and Yai (2000) analyzed the steel structure and windows of passenger car bodies under transient pressure impact loads and assessed the ability of existing vehicles on existing lines to withstand train rendezvous pressure waves. Qian, Zheng, and Yu (2013) used the finite element method to simulate the dynamic response process of high-speed train carriages under the action of pressure waves generated by the rendezvous of bright lines at different speeds, and obtained the variation curve of the equivalent force at the center of the side windows with time. Wang (2020) studied the dynamic stress response characteristics of the driver's cab side window glass in crossing the Qinling tunnel and proposed an optimization scheme for glass structure improvement. Liu, Qi, and Wan (2022) conducted a strain dynamic response and maximum principal stress test on the glass of high-speed trains during traversing the tunnel, and analyzed the load-bearing characteristics of the glass of high-speed trains under the action of pneumatic loads.

The traditional glass strength design method for high-speed trains is mainly based on the relevant standards for static strength and dynamic wind pressure fatigue action testing, which is difficult to truly reflect the adverse effects of the actual line on the glass vibration of high-speed trains. In order to effectively grasp the change law of vibration fatigue on the glass life of high-speed trains, the study of the vibration response characteristics of high-speed train glass in the actual line state has become one of the important elements of high-speed train glass reliability and life design. This study is conducted to measure the lateral vibration acceleration response of the glass of high-speed trains in the process of traversing the tunnel, in order to accurately understand the time course of the vibration acceleration of the train glass and its influencing factors in the process of traversing the tunnel, and to provide a data reference basis for the analysis of force characteristics, damage mechanism, strength design and structural optimization of high-speed train glass.

2. Vibration acceleration measurement

2.1 Test subjects

Beijing-Chengdu high-speed railway line CR400BF-A, 2 group of 16 sections of passenger compartment window glass for testing, glass length and width dimensions of 1480mm × 800mm, the glass under test from the head of the train distance of about 30m (located in the second car) structure schematic diagram is shown in [Figure 1\(a\)](#). Trains through the tunnel for the two-line passage tunnel, which is mainly concentrated in Zhengzhou - Xi'an section (average speed of 300km/h) and Xi'an - Chengdu section (average speed of 250km/h).

2.2 Test equipment and parameters

The portable INV3062T0 24-bit high-precision data acquisition instrument is used, and the acquisition frequency is 1024K during the actual measurement; the acceleration sensor is used to pick up the vibration with an accuracy of 50mV/g (g is the acceleration of gravity); the DASP-V11 engineering version dynamic test and signal analysis software (including signal oscillation and acquisition, signal generation and DA output, basic signal analysis, etc.) is used for analysis, and the vibration acceleration waveform graph and frequency response function curve can be obtained.

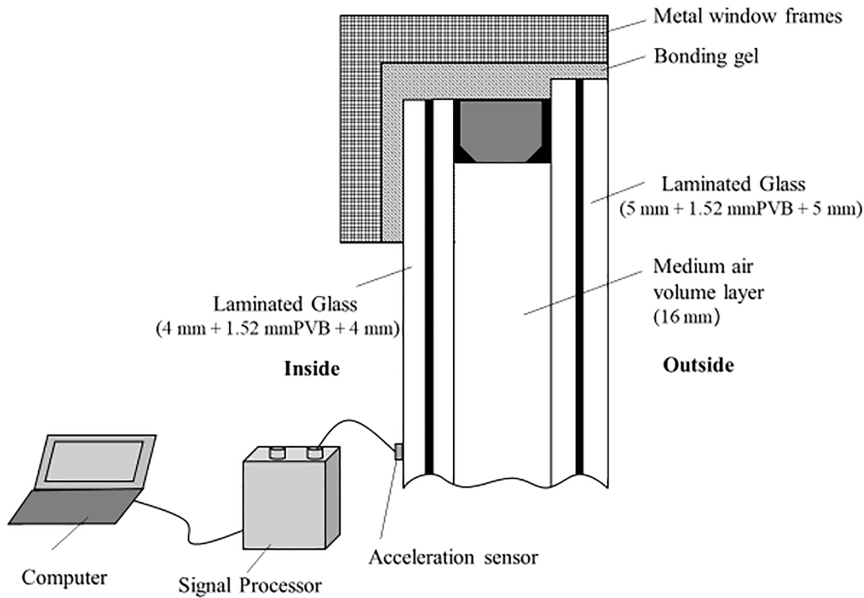
2.3 Testing process

The glass of the passenger compartment window on the side near the tunnel wall is selected for measurement. As shown in [Figure 1](#), the vibration acceleration sensor is pressed against the surface of the glass of the passenger compartment towards the center of the plate on the inside of the car to pick up the vibration, and the time course curve of the vibration acceleration of the measured glass is obtained in real time through the signal collector and analysis software. Before the test, the acceleration values were zero-drifted to eliminate other influencing factors before the test. The lateral vibration acceleration response of the passenger compartment window glass when the high-speed train enters the tunnel entrance, traverses the tunnel exit, traverses the whole tunnel, traverses the tunnel group, and meets in the tunnel were tested respectively.

3. Results and discussion

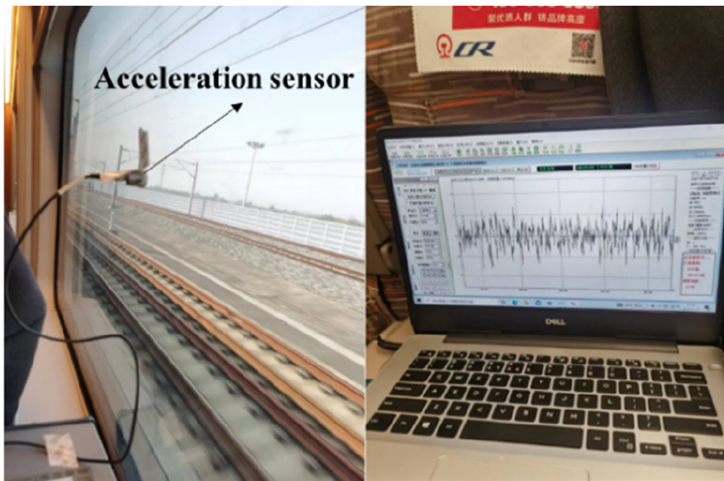
3.1 Acceleration response history of lateral vibration of passenger compartment window glass

3.1.1 In and out of the tunnel entrance and through the entire tunnel. The dynamic response curve of the measured transverse vibration acceleration of the glass with time during the time when the train enters the tunnel entrance from outside the tunnel (open line) is shown in [Figure 2\(a\)](#). As shown in the figure, the vibration acceleration increases to the maximum value



Schematic diagram of glass structure and acceleration test

(a)



Field test photo

(b)

Figure 1. Measured field diagram of transverse vibration acceleration. **Source(s):** Authors' own work

and stabilizes within 5s after the train glass enters the tunnel, and its amplitude is significantly larger than the corresponding acceleration amplitude when walking outside the tunnel, which shows that the vibration increases significantly after the train enters the tunnel.

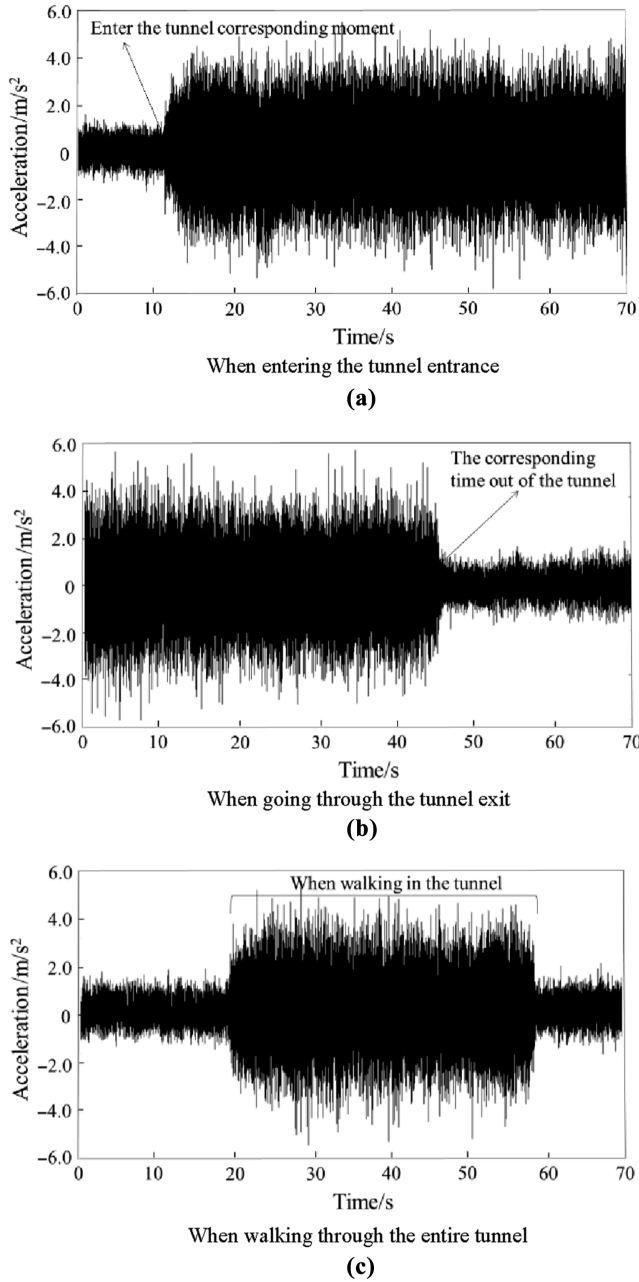


Figure 2. Transverse vibration acceleration response of passenger compartment window glass when entering and exiting the tunnel entrance and crossing the whole tunnel. **Source(s):** Authors' own work

The dynamic response curve of the lateral vibration acceleration of the measured glass with time when the train traverses the tunnel exit is shown in [Figure 2\(b\)](#). In the figure: the glass under test is out of the tunnel entrance at about 43 s. The test results show that the transverse

vibration acceleration of the glass under the test after leaving the tunnel is basically the opposite of the situation when entering the tunnel entrance, and after leaving the tunnel, the vibration acceleration amplitude of the glass under test rapidly decreases and stabilizes to the level before entering the tunnel. Figure 2(c) records the measured glass transverse vibration acceleration response history during the process of traversing the whole tunnel (about 3,000 m long), and it can be seen from the figure that the measured glass vibration acceleration amplitude has been stabilized during walking in the tunnel, indicating that the high-speed train glass vibration is not affected by other factors when walking in the tunnel.

3.1.2 *When crossing the tunnel complex.* Tunnel group refers to a group or group of tunnels where the spacing between adjacent tunnel openings is less than the length of a passenger train, in mountainous areas, high-speed railroads generally use tunnel groups through mountainous areas. The acceleration response of the measured glass is shown in Figure 3(a) when the train traverses a cluster of seven tunnels and briefly crosses the gap between adjacent tunnel openings. In this figure: the train crosses the tunnel complex for six consecutive short periods at 75, 330, 580, 800, 960, and 1,000 s, respectively, through the gap between adjacent tunnel openings. The longest tunnel is about 15 km and the shortest is about 2,500 m. As can be seen from the figure, regardless of the length of the tunnel, the amplitude of vibration acceleration is

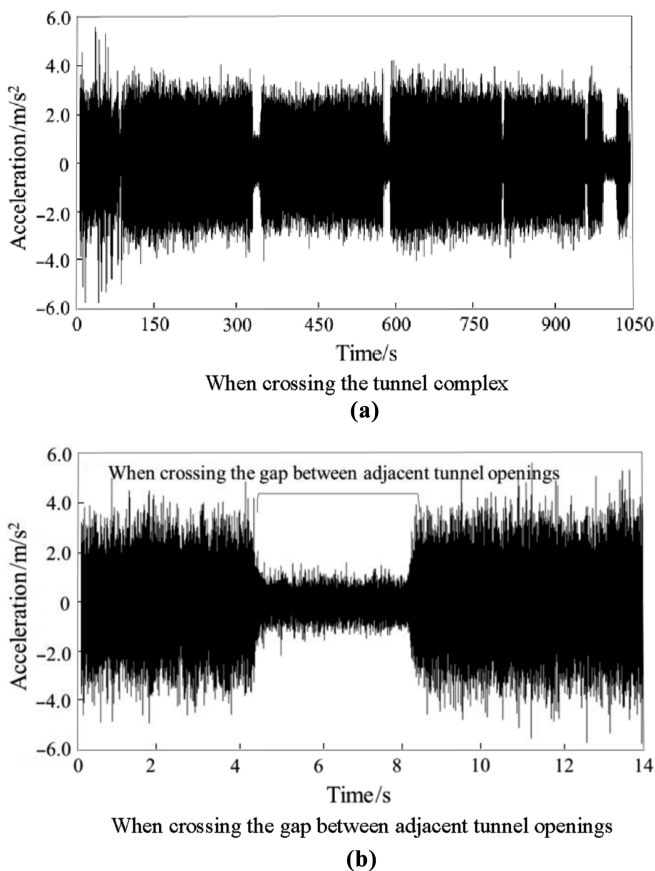


Figure 3. Transverse vibration acceleration response of the measured glass when passing through the tunnel group and the gap between adjacent tunnel openings. **Source(s):** Authors' own work

basically the same for walking in the tunnel at the same travel speed and does not change significantly in the tunnel, indicating that the length of the tunnel has little effect on the vibration acceleration. [Figure 3\(b\)](#) shows the fine variation of the vibration acceleration response of the measured glass at the gap between two adjacent tunnel openings through the tunnel cluster, showing that the vibration acceleration during this process rapidly decreases to a value comparable to that corresponding to walking outside the tunnel, and does not vary with the length of the gap between the two adjacent tunnel openings. The test results also show at the same time that the vibration acceleration of high-speed trains through the tunnel is not subject to significant transient changes due to the tunnel aerodynamic effect as the glass surface strain.

3.1.3 When meeting traffic in the tunnel. The lateral vibration acceleration response of the measured glass is shown in [Figure 4](#) when both trains travel at an average speed of 250 km/h to meet in the tunnel. From the figure can be seen: in the measured glass and the opposite direction after the rendezvous of its vibration produced significant fluctuations in the process of change. The maximum vibration acceleration is about 2.5 times higher than before the meeting, and the maximum vibration acceleration occurs at the moment when the measured glass intersects with the head of the train in the opposite direction.

3.2 Effect of travel speed on vibration acceleration amplitude

[Figure 5\(a\)](#) records the course of the measured glass transverse vibration acceleration with time during the continuous deceleration of the train in the tunnel, which shows that the measured glass vibration acceleration amplitude becomes smaller as the travel speed becomes slower. [Table 1](#) gives the measured transverse acceleration amplitudes and their ratios for the measured glass in and out of the tunnel at different travel speeds. [Figure 5\(b\)](#) shows the measured curves of the measured transverse acceleration amplitude of the measured glass in the tunnel and outside the tunnel during the traveling process and the traveling speed. The above test results show that when the travel speed exceeds 150km/h, with the increase of travel speed, the acceleration amplitude of vibration of the tested glass in the tunnel is significantly higher than that outside the tunnel, meaning that the ratio is increasing, indicating that with the increase of travel speed, the vibration of the glass in the tunnel of high-speed trains is significantly increased, which is more likely to lead to its sudden rupture.

3.3 High-speed train glass transverse vibration frequency response characteristics

The typical transverse vibration acceleration response curves of high-speed train glass in and out of the tunnel at the same travel speed are shown in [Figure 6](#), which exhibit typical harmonic vibration characteristics. As the high speed of the train intensifies the complexity of the load

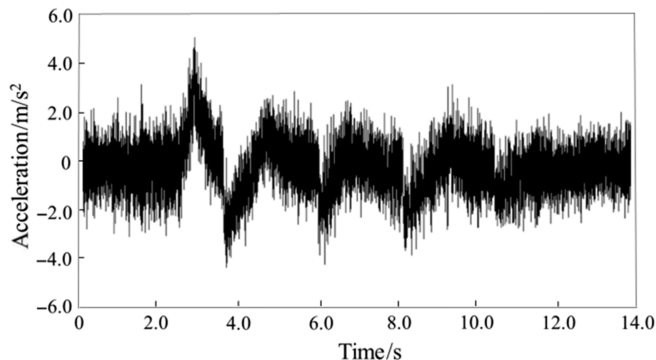
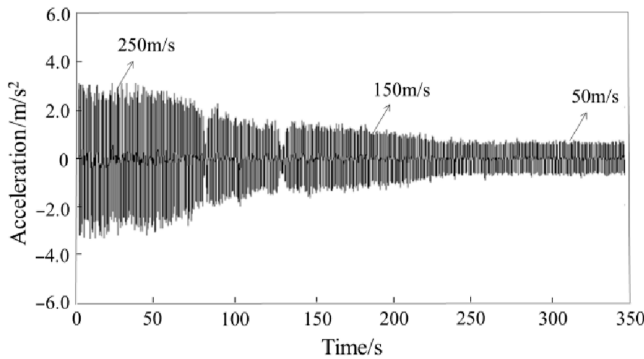
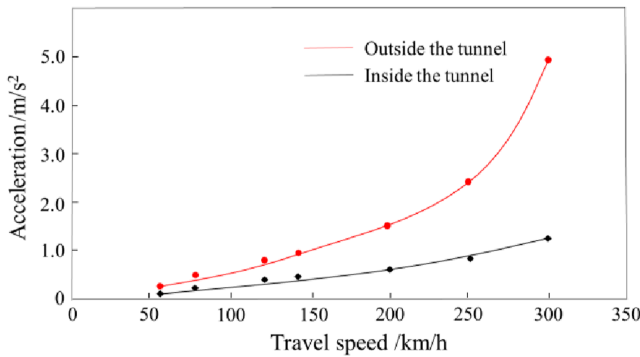


Figure 4. Transverse vibration acceleration response of passenger compartment window glass during meeting in the tunnel. **Source(s):** Authors' own work



Acceleration response of measured glass transverse vibration during continuous deceleration in tunnel

(a)



The relationship between the train speed and the measured glass transverse vibration acceleration amplitude curve

(b)

Figure 5. The effect of train travel speed on lateral vibration acceleration. **Source(s):** Authors' own work

Table 1. Transverse vibration acceleration values (m/s^2) and their ratios for the measured glass inside and outside the tunnel at different traffic speeds

Speed(km/h)	Travel position		Ratio
	In the tunnel	Outside the tunnel	
55	0.30	0.13	2.31
75	0.46	0.21	2.20
120	0.88	0.44	2.00
140	1.00	0.47	2.13
200	1.60	0.50	3.2
250	2.50	0.80	3.12
300	5.04	1.10	4.58

applied to the car body, it will lead to a mismatch between the inherent vibration frequency of the car body and the excitation frequency of the load applied, which intensifies the vibration of the car body and the glass of the high-speed train (Yu, 2018), therefore, the excitation frequency of the load applied to the car body during travel should be avoided to resonate with

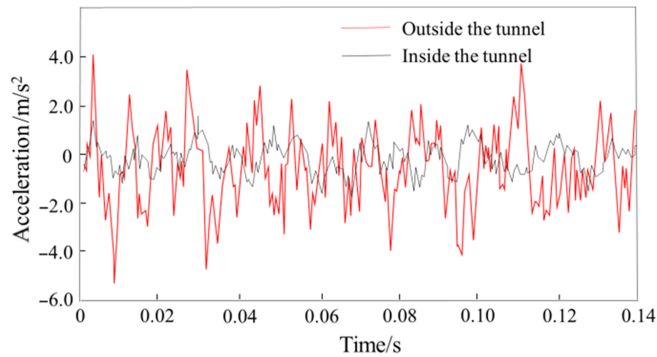


Figure 6. Typical lateral vibration acceleration response of traffic inside and outside the tunnel. **Source(s):** Authors' own work

the same or equivalent to the inherent frequency of the car body and its components. By performing Fast Fourier Transform waveform analysis on the vibration signals obtained from the acceleration sensors, the frequency distributions of the measured glass at different travel speeds inside and outside the tunnel were obtained, and the frequencies of the main distributions were found to be basically the same. A typical frequency response function curve of the measured glass vibration is shown in Figure 7, and the main frequencies contain 24, 36, 116, 182 Hz, etc.

The glass is struck vertically with a single trigger excitation of the force hammer, and the force and acceleration signals are Fourier transformed to obtain the vibration acceleration response of the glass under test with the trigger excitation and its corresponding frequency response function curves in Figure 8(a) and Figure 8(b), from which the free vibration intrinsic frequency (fundamental frequency) of the glass under test is 116 Hz (corresponding to the third frequency value in Figure 7).

3.4 High-speed train glass vibration power amplification factor

Under the action of harmonic load, forced vibration, according to D'Alembert's Principle (D'Alembert's Principle) of the "kinematic method" theory, the "inertia force" is applied to the structure, the dynamic problem can be transformed into a static problem to solve.

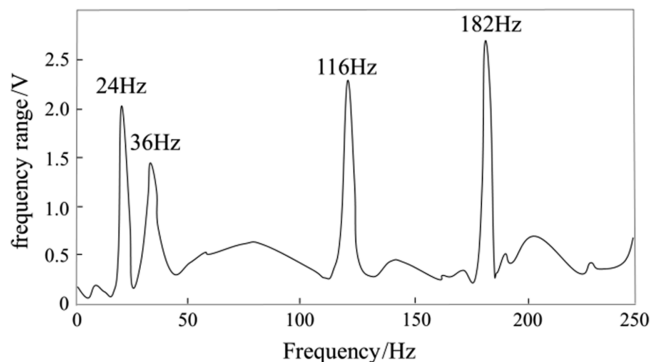


Figure 7. Typical frequency response function curve of the measured glass transverse vibration during the driving process. **Source(s):** Authors' own work

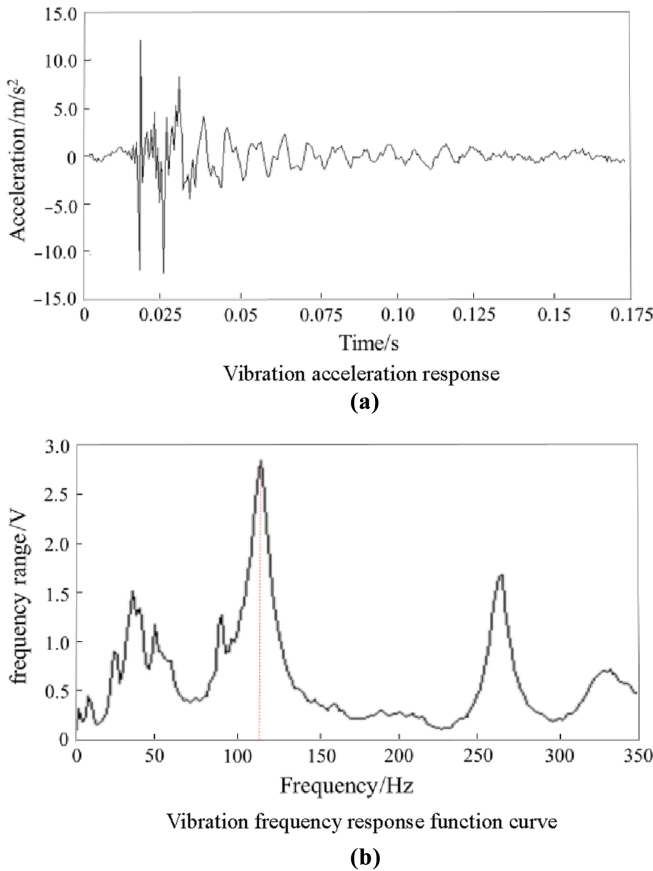


Figure 8. Acceleration response and vibration frequency response function curve of the measured glass under single trigger excitation. **Source(s):** Authors’ own work

The harmonic load imposed on the glass by a high-speed train is transmitted from the edge frame to the glass, and the resulting lateral vibration acceleration is applied perpendicular to the glass surface as an “inertial force” and produces a bending vibration stress on the glass surface. Through the actual measurement shows that the lateral vibration acceleration does not change due to the change of position on the glass plane. Therefore, the “inertia force” caused by the transverse vibration is uniformly distributed in all parts of the glass plane, as shown in Figure 9, the inertia force can be considered as a uniform load acting on the glass plane.

The uniform “inertia force” acting on the glass of a high-speed train under transverse vibration as a function of time is as follows:

$$q(x, y) = q_0(t) = \Delta m a_{\max} \sin(\theta t) = \rho h a_{\max} \sin(\theta t) \tag{1}$$

where q_0 is the uniform load, Δm is the mass per unit area of the glass, ρ is the bulk density of the glass, h is the thickness of the glass, a_{\max} is the vibration acceleration amplitude, θ is the harmonic load frequency, and t is the vibration response time.

Under the action of the uniform “inertia force” as above, the resulting maximum bending tensile stress in the glass of high-speed trains is distributed in the center of the plate, and its relationship with time is as follows.

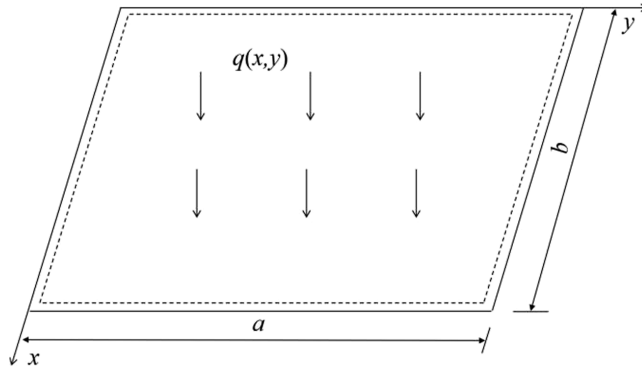


Figure 9. Schematic diagram of “inertial force” distribution of glass in high-speed trains under transverse vibration. **Source(s):** Authors’ own work

$$\sigma(t) = f \frac{q_0(t)b^2}{h^2} = f \frac{\rho a_{\max} b^2}{h} \sin(\theta t) \tag{2}$$

where f is the coefficient, which is related to the length and width dimensions of the glass, as shown in Table 2 (Noel, 1997), and b is the width of the glass.

According to equation (2), the maximum static stress under static action can be obtained as:

$$\sigma_{s\max} = f \frac{\rho a_{\max} b^2}{h} \tag{3}$$

The solution of the dynamic stress in the smooth phase of the high-speed column under the harmonic load of the forced vibration of the car can be expressed as [24]:

$$\sigma_d(t) = \sigma_{s\max} \frac{1}{1 - \frac{\theta^2}{\omega^2}} \sin \theta t = |\beta| \sigma_{s\max} \sin \theta t \tag{4}$$

where $\sigma_d(t)$ is the dynamic stress at moment t and ω is the intrinsic frequency of the glass (fundamental frequency). $|\beta|$ is the dynamic amplification factor:

$$|\beta| = \sigma_{d\max} / \sigma_{s\max} = \frac{1}{1 - \frac{\theta^2}{\omega^2}} \tag{5}$$

According to equation (5), the relationship $|\beta|$ with θ/ω can be obtained as shown in Figure 10. Clearly, when the high-speed train glass forced vibration harmonic load vibration frequency is closer to its inherent vibration frequency, resulting in a greater dynamic amplification coefficient, the greater the harm, and when t is very large, the harmonic load changes quickly, the glass is too late to respond, the solid brought about by the impact is also

Table 2. f

a/b	1.0	1.2	1.4	1.6	1.8
f	0.2874	0.3762	0.4530	0.5172	0.5688
a/b	2.0	3.0	4.0	5.0	∞
f	0.6102	0.7134	0.7410	0.7476	0.7500

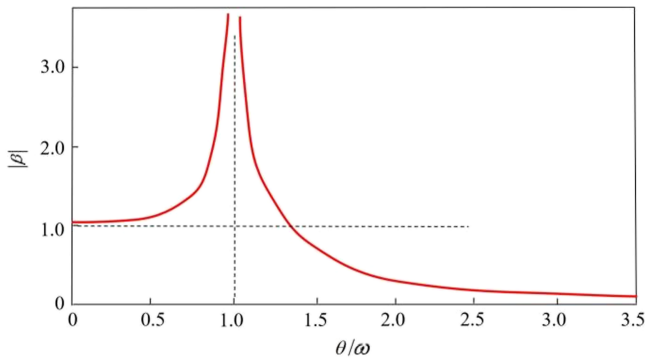


Figure 10. $|\beta|$ vs θ/ω relationship curve under harmonic load. **Source(s):** Authors' own work

very small. Therefore, the actual design of the glass structure of high-speed trains should try to avoid its intrinsic frequency value and the vibration frequency value of the harmonic load close or equal. According to the measured results in Figures 7 and 8(b), the values of the forced vibration simple harmonic load vibration frequencies closest to the measured glass intrinsic frequency value (116Hz) are 36Hz and 182Hz, respectively, and the corresponding dynamic amplification coefficients can be calculated as 1.11 and 0.68, respectively, according to equation (5).

Taking the measured glass in this paper as an example for calculation, the maximum acceleration amplitude corresponding to the travel speed of 300km/h is 5.04m/s^2 according to Table 1, the maximum static stress is 5.62MPa according to equation (3), and the maximum dynamic amplification factor is 1.11 according to equation (5), therefore, the maximum dynamic stress corresponding to this time can be calculated as 6.18MPa. As the dynamic stress is a bad stress, the distribution of the glass surface and internal defects are very sensitive to it and is often the starting source of glass rupture. Therefore, the dynamic stress value should not exceed the design value of the dynamic fatigue strength of high-speed train glass.

4. Conclusion

- (1) Through the tunnel process, the vibration of high-speed train glass significantly increased, and with the increase in travel speed, the measured glass in the tunnel transverse vibration acceleration amplitude increase rate is significantly higher than outside the tunnel, that is, the ratio of increasing, thus more likely to cause high-speed train glass breakage.
- (2) Traveling in the tunnel, when the high-speed train glass transverse vibration will not change with the length of the tunnel, and will not be affected by the role of the tunnel aerodynamic effects, but when the rendezvous with the opposite direction of travel, its transverse vibration will produce significant fluctuations in the process of change.
- (3) During travel, high-speed train glass exhibits typical harmonic vibration characteristics, and the excitation frequency of its load does not change with the train travel speed and travel position (inside and outside the tunnel).
- (4) High-speed train glass is subjected to lateral vibration acceleration by a kind of "inertial force" perpendicular to the surface of the glass uniformly applied to the glass, and generates bending cycle vibration stress, which is prone to fatigue damage.

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Further reading

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