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Noise Characteristics and Noise Control of a Suspended Aerial Rail Train

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Abstract

Compared with the conventional rail transit, the suspended aerial rail train has a big difference in the vehicle structure, which shows the uniqueness in the vehicle noise, so it has an important research value. In this paper, we investigate the vibration noise characteristics of the suspended aerial rail train based on the "source-path-receiver" model. We design a low-noise scheme to control the vehicle noise, and use the statistical energy approach (SEA) to establish a noise simulation prediction model. The model is verified by noise tests to be in high agreement with the actual situation. Suspended aerial rail trains have significant advantages over conventional rail transit vehicles in terms of noise control, which helps to better meet noise standards and ensure stable operation.

Keywords: suspended aerial rail train, source-path-receiver, vibration-noise characterization, low noise design, vehicle noise simulation prediction, noise line test validation.

1 Introduction

Recently, the suspended aerial rail train "Guanggu Guangzi" developed by CRRC Qingdao Sifang Co., Ltd. has begun to carry passengers on the Wuhan Guanggu Air Rail Tourism Line. This marks the first time that China's aerial rail train has been commercially utilized, details of which are shown in Figure 1.

Figure 1: Suspended aerial rail train "Guanggu Guangzi".

Suspended aerial rail trains, refers to its walking part in the track beam, and the vehicle structure is suspended in the walking part of the lower part of the "air train". Suspended vehicles originated in 1825 in the United Kingdom, the original passenger suspended monorail transportation using wooden track, by horse power traction [1]. Currently, there are four main types of suspended monorail trains around the world based on the structure of the traveling section [2]:

a. Asymmetric suspended steel wheel, steel rail type

This model is designed by German Longines, so it is called Longines type. The main features include steel rails mounted on steel truss beams, wheel bogies running along the rails, carriages suspended below the truss beams, and suspension members set on one side of the track beams.

b. "I"-shaped track beam suspension type

This model is characterized by a track beam with an "I" cross-section and wheels embedded in the beam. The wheels are made of special materials to withstand the weight and are driven by a chain-driven motor. Although this type of monorail has a simple structure and is widely used in entertainment and tourist attractions in various countries, it is not suitable for urban rail transportation due to high vibration and low capacity.

c. Asymmetrically suspended rubber-wheel type

This is an improved version of the Wuppertal monorail, characterized by asymmetric suspension, with the suspension members located on one side of the track beam. The steel wheels on the bogie are eliminated in favor of rubber tires. The bogie is equipped with running and guide wheels. The running wheels are located on the track girders for load bearing, traction and braking, while the guide wheels are located on both sides of the track girders for guidance and reduction of transverse vibrations.

d. SAFEGE type

The SAFEGE type, by far the most widely used suspended monorail vehicle, is characterized by symmetrical suspension and was originally designed in France. Features include steel box-type track beams with openings at the bottom, in which two-axle bogies carrying rubber tires run inside the track beams, complete with walking and guide wheels. This type is used on several lines, such as the Chiba and

Shonan lines in Japan, and the Dortmund University and Düsseldorf Airport lines in Germany.

The design of the "Guanggu Guangzi " aerial rail train is similar to that of the SAFEGE type, with a bogie consisting of a frame, rubber tires, air springs, rocking sleepers, traction and braking devices, etc. The running wheels are driven by longitudinal traction motors using a disc-shaped braking system, with brake discs mounted on the motor's rotating shaft. Each corner of the frame is equipped with a guide wheel, whose function is similar to that of the asymmetric suspended rubber wheel type, and is equipped with a spare wheel to ensure safety. The Series II suspension was air-sprung, with the rockers located between the two air springs. The suspension members of the body are connected to the rockers through a hole in the center of the frame. The suspension elements consist of suspension rods, suspension tubes and safety cables, the latter ensuring safety in the event of damage to the rods. The suspension members are connected to the car body and the bogie through openings in the bottom of the box girder. The turnout is a movable track inside the box girder, and the change of train direction is realized by the horizontal movement of the track.

Suspended aerial rail train have a number of advantages over traditional rail vehicles:

a. Smaller space occupation

The track is mainly located in the air, which reduces the occupation of the ground, saves urban space and is suitable for complex or narrow terrain.

b. Lower construction cost

Compared with subway, the suspended aerial rail train costs less, without large-scale underground excavation and tunnel support.

c. Low noise pollution

Unique suspension structure makes the noise lower than traditional ground rail transportation.

d. Small environmental impact

Less interference with natural landscape and urban environment, especially in ecologically sensitive areas.

e. Safety

These trains have high safety performance because they are far away from ground transportation and pedestrians.

f. High adaptability

Suitable for various terrains, such as mountainous areas, rivers and built-up areas.

g. High energy efficiency

Usually powered by electricity, which is more energy efficient and has lower carbon emissions compared to fuel-driven.

The " Guanggu Guangzi " aerial rail train is equipped with fully automatic driving function, realizing a high degree of intelligence, including intelligent sensing and intelligent driving. In terms of design, it follows the principle of high efficiency and energy saving, and applies lightweight body, permanent magnet motor, frequency conversion air conditioning and other technologies to reduce the per capita energy consumption of 100 kilometers by 15%. At the same time, taking into account the transportation capacity and low-carbon environmental protection, the train also focuses on passenger comfort. Therefore, the program design stage focuses on controlling noise indicators, implementing vehicle structural noise reduction and sound source control to comply with relevant standards and technical requirements [3], and ensuring low-noise design and stable operation of the entire vehicle.

2 Noise Source and Transmission Characterization

According to the theoretical research and engineering experience of rail transportation noise at home and abroad [4], vehicle noise mainly comes from traction noise, wheel-rail noise and pneumatic noise. The proportion of these noise sources varies with the operating speed, as shown in Figure 2. The operating speed of the suspended aerial rail train is 60 km/h, so its main noise source is wheel-rail noise, followed by traction noise, while the pneumatic noise is relatively small and can be ignored.

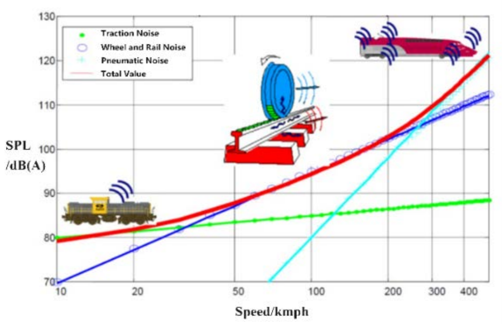

Figure 2: Rail vehicle noise sources and speed partitioning.

Considering the propagation path of sound, it can be categorized into direct airborne sound, air-structure coupled sound, and structural sound depending on the mode of excitation and response, as detailed in Figure 3.

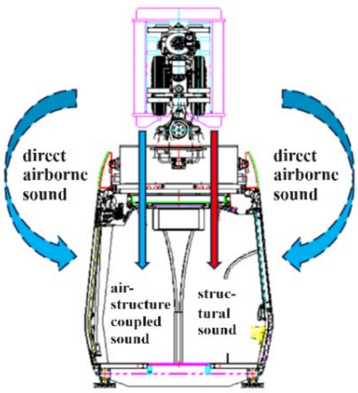

Figure 3: Noise propagation pathways for suspended aerial rail trains.

For direct airborne sound, attention should be focused on the weak parts such as doors and windshields. As the short mechanism sliding doors and folding shed windshields usually used in rail vehicles ensure good sealing at low and medium speeds, the direct airborne sound from outside to inside the vehicle can be ignored; air-structure coupled sound in the vehicle is manifested as the coupling of vibration of the interior panels with the acoustic field, so it is necessary to focus on strengthening the sound isolation performance of the structure. As the walking part and electrical equipment are located on the roof, the sound insulation performance of the roof directly affects the contribution of sound sources to the noise inside the vehicle; the proportion of structural sound is related to the vibration damping capability of the walking part, which is reflected in the energy attenuation from the external vibration source to the vibration of the interior panel inside the vehicle; according to the vibration sound radiation principle, the vibration energy of the interior panel is reduced, which in turn lowers the radiation noise.

3 Low Noise Structural Design

According to the vibration noise transmission characteristics analyzed in the previous section, the low noise design of the suspended aerial rail train is mainly reflected in the following aspects.

3.1 Multi-stage damped suspension bogie

The suspension bogie system consists of a frame, rocking sleepers, running wheels, guide wheels, series I suspension and drive units, series II suspension and central traction units. Unlike conventional rail vehicles, the running wheels of the suspended vehicle use pneumatic rubber tires to replace the rigid wheels (see Figure 4). This design significantly reduces wheel stiffness and effectively minimizes vibration caused by relative wheel-rail displacement.

Figure 4: Comparison of conventional traveling wheel (left) and suspended traveling wheel (right).

As an example, for a subway line in China, the comparison of the vertical vibration acceleration of the axle of a rigid wheel and that of a rubber wheel at the same speed of 60 km/h is demonstrated in Figure 5. The results show that the rubber wheel has a significant reduction in vibration energy in all frequency bands compared to the rigid wheel, with an overall reduction of about 43%.

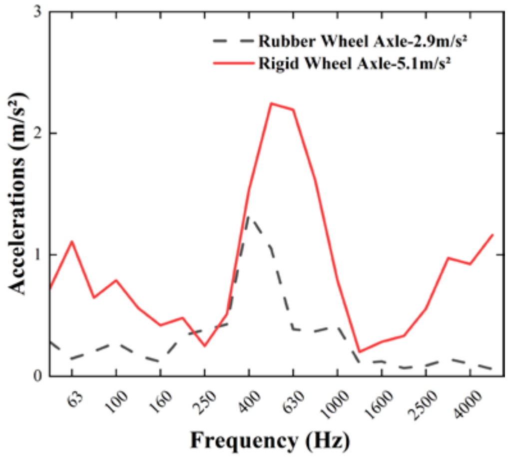

Figure 5: Comparison of axle vibration acceleration.

Wheel-rail vibration energy was transferred through the frame, rocker, and body to the interior panels, and the forced vibration of the interior panels subsequently radiated noise outward. The vertical vibration acceleration of each part (see Table 1) showed that the vertical vibration acceleration of the interior roof panel was attenuated by at least 94% compared to the vibration source after damping by the multi-stage suspension device. Overall, the multi-stage damped suspension bogie effectively reduces the energy transfer from the vibration source to the interior through the structure, and reduces the coupling between the interior panel vibration and the sound field inside the vehicle.

Part	Vertical acceleration [m/s²]	Vibration attenuation rate [%]
Wheel axles	5.8	0
series I suspension	1.9	67
series II suspension	0.56	90
Interior top panel	0.37	94

Table 1: The vertical vibration acceleration of each part.

In suspended "vehicle-rail" systems, thin-walled steel box girders with openings in the lower part are often used instead of I-beams in conventional rail lines (see Figure 6). The bogie traveler system is covered by the steel box girders, which form a nearly confined space with a fully reflective boundary wall, which results in the formation of a reverberant field inside the box girders to amplify airborne excitation while effectively suppressing the transmission of transmitted sound, and at the same time, the design significantly reduces the energy of the acoustic field outside of the steel box girders. As a result, in the bogie region, the "suspended vehicle-steel box girder" system exhibits wheel near-field sound enhancement and body near-field sound attenuation, which is significantly different from the wheel-rail noise characteristics of conventional rail vehicles.

Figure 6: Steel box girders.

According to Table 2, at the same speed, the noise in the bogie area on the body side of general subway vehicles, which is subject to the superposition of the four sets of wheel rails, motors and gearboxes, is 2 dB higher than that on the wheel side; and the noise of the suspended aerial rail train in the bogie area on the body side, compared with that on the wheel side in the Steel box girders, is 12 dB lower.

Part	Noise of suspended aerial rail train [dB(A)]	Noise of general subway vehicles [dB(A)]
Close to the wheel	105	104
Close to the body	93	106

Table 2: Comparison of noise values at the same speed.

Spectral analysis shows that in 60 km/h operation, the sound field environment of the suspended aerial rail train near the body side at 630 Hz (the main frequency of subway wheel-rail noise) is 15 dB lower than that of conventional subway vehicles, see Figure 7. While maintaining the same top-level targets for interior noise, the requirements for vehicle sound insulation performance are correspondingly reduced due to the reduction of airborne sound sources, thus providing greater design flexibility for noise control.

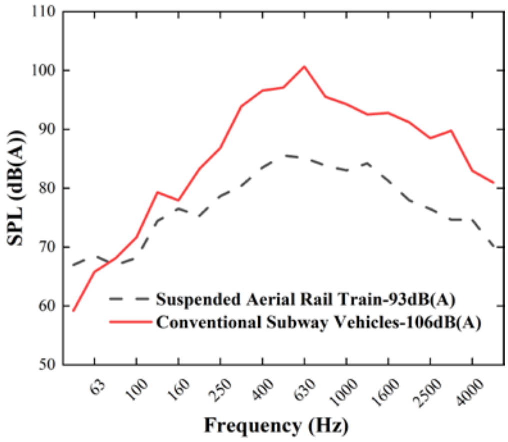

Figure 7: Body side noise comparison.

3.2 Composite roof section structure

The top section of the suspended aerial rail train is a composite of two structures, which are shown in detail in Figure 8, with the diagonal ribbed body hollow profile section on the left and the straight ribbed body hollow profile section on the right.

Figure 8: Composite roof section structure.

The sound insulation amount of the diagonal rib section is 36dB, mainly used in the bogie area, which not only improves the tensile load resistance, but also enhances the sound insulation performance; the sound insulation amount of the straight rib section is 31dB, which is used in the middle area of the passenger compartment, and is suitable for environments where the sound source outside the vehicle is small, and the processing technology is simple. The spectral distribution of sound insulation is shown in Figure 9.

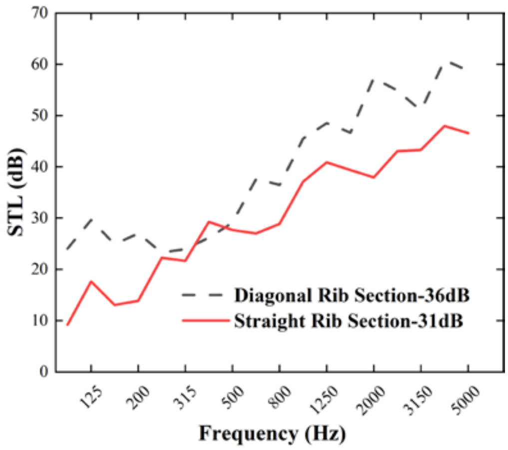

Figure 9: Composite roof section sound insulation curve.

Research [5] shows that in the frequency band above 500 Hz, the greater the angle α between the rib and skin of the profile, the better the sound insulation. The angle of the diagonal rib profile is currently 44°, but optimization to 60° will increase the total sound insulation and thus reduce the interior noise.

3.3 Air conditioning ventilation system design

In the stationary state, the interior noise mainly comes from the radiated noise of the roof equipment and the aerodynamic noise of the air supply and return vents of the air conditioner. The air outlet noise is mainly radiated by the structure and air vibration caused by the turbulence generated by the airflow through the air outlet and air duct surface. The use of decentralized return air in the suspended vehicle reduces the turbulence noise generated by the high-speed airflow through the centralized return air outlet. The noise of the air conditioning system of the suspended vehicle is also lower than that of the conventional centralized return air system due to the lower total airflow index [6]. According to Table 3, the interior noise of the suspended vehicle in the static state is 5 dB lower than that of general subway vehicles.

Part	Noise of suspended aerial rail train [dB(A)]	Noise of general subway vehicles [dB(A)]
Interior noise	60	65

Table 3: Comparison of static interior noise values.

4 Vehicle Noise Simulation Prediction

Simulation prediction of in-vehicle noise was performed using the statistical energy approach (SEA). According to the external noise sources and vehicle structure, the suspended vehicle was divided into subsystems such as driver's compartment, front of passenger compartment, middle of passenger compartment and rear of passenger compartment, and the whole vehicle acoustic simulation model was established, which is shown in Figure 10.

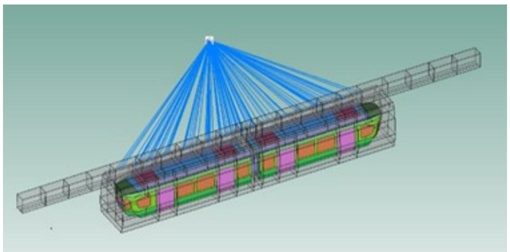

Figure 10: Vehicle acoustic simulation model.

The energy balance equation between the subsystems is expressed as [7],

$$\omega\eta_i E_i + \sum_{j=1,j\neq i}^{n} \omega\eta_{ij} E_i - \sum_{j=1,j\neq i}^{n} \omega\eta_{ij} E_j = P_{\text{in},i}, i = 1,2,3,\cdots \quad (1)$$

where $P_{\text{in},i}$ is the input power of subsystem i, E_i is the energy of the respective subsystem, ω is the angular frequency, and η_{ij} is the coupling between subsystems i and j $(i \neq j)$, and η_i is the dissipation loss factor of subsystem i.

The coupling loss factor as well as the individual subsystems can again be expressed as [7],

$$\eta_i = \frac{c_0 S_i \alpha_i}{4\omega V_i} \quad (2)$$

$$\eta_{ij} = \frac{c_0 S_{ij} \tau_{ij}}{4\omega V_i} \quad (3)$$

where c_0 is the speed of sound, S_i is the total surface area of subsystem i, α_i is its average absorption coefficient, V_i is the volume of subsystem i, $S_{ij} = S_{ji}$ is the area of the interface between acoustic cavity i and acoustic cavity j, and τ_{ij} is the transmittance coefficient at this interface.

The average absorption coefficient for each subsystem can again be expressed as [7],

$$\alpha_i = \frac{55.26V}{c_0 T_{60} S} \tag{4}$$

where, V is the total volume of the train compartment, T_{60} is the reverberation time, and S is the total internal absorbing surface.

Parameters such as external sound source, vehicle sound insulation, and dissipation loss factor are input to the simulation prediction model to calculate the average sound pressure level of each subsystem. The final distribution results of the sound field inside the vehicle are shown in Figure 11.

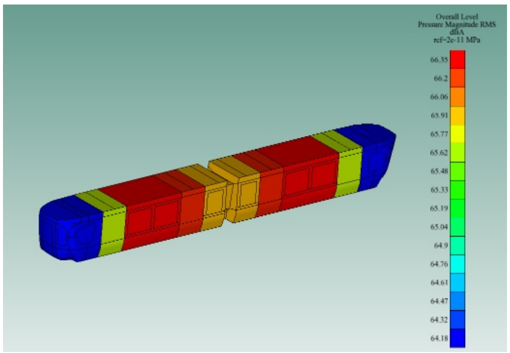

Figure 11: Simulation prediction results.

The simulation results show that the predicted noise level inside the vehicle is 64~66 dBA at 60 km/h, which is much lower than the design index and the noise level of conventional subway vehicles. However, the noise levels in the middle and rear of the passenger compartment are relatively high, which is due to the low sound insulation in the middle roof section and windshield, which are the weak points of the vehicle's sound insulation capability, and there is room for further optimization.

5 Noise Line Test Validation

A noise line test of the suspended vehicle was conducted to check whether the noise level complied with the noise reduction design specification and to verify the accuracy of the simulation prediction model. During the test, all doors of the train are closed to ensure that the train is in a state of readiness and there are no other passengers except for the test personnel, the train is started and all auxiliary electrical equipment is turned on, the train is accelerated to 60km/h and the speed is maintained in the range of 60±5%km/h. After entering the test speed range, the noise at each point is measured and the time data is recorded, each measurement point lasts 20 seconds, and three valid measurements are made in total. Each measurement point lasts for 20 seconds, and 3 valid measurements are made in total [8].

Select the test object vehicle and arrange standard measurement points to test the noise level inside the vehicle. One measurement point, No. MC_0, with a height of 1.2 m, is arranged in the driver's compartment of the MC vehicle, and three measurement points, No. MC_1, MC_2 and MC_3, are arranged in the passenger compartment, located at the longitudinal centerline of the vehicle body, with a height of 1.5 m. For details, please refer to Figure 12.

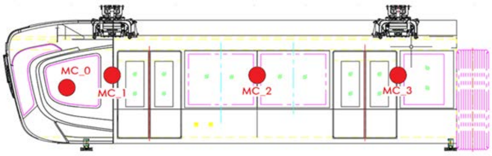

Figure 12: Noise measurement point arrangement.

Based on the test arrangement scheme, the calculation results of the corresponding field points in the simulation model were selected and these predicted values were compared with the actual test values, as detailed in Table 4.

Result	Driver's compartment [dB(A)]	Front of passenger compartment [dB(A)]	Middle of passenger compartment [dB(A)]	Rear of passenger compartment [dB(A)]
Predicted value	64	66	66	66
Test value	65	67	66	68

Table 4: Comparison of simulation and test results.

The test results show that the noise level inside the suspension vehicle is low and the sound field distribution is uniform, which is in line with the design index. The simulation calculation results are highly consistent with the measured values, indicating that the simulation model has good prediction accuracy.

6 Conclusions and Contributions

This paper analyzes in detail the noise source and propagation characteristics of the suspended air rail train, and introduces the low-noise structural design adopted in the program design stage, establishes a whole-vehicle noise simulation model to predict the noise in the suspended vehicle, and verifies the accuracy of the simulation results through the noise line test. The results show that the noise level of the suspended air rail train is significantly better than that of the conventional rail vehicle and effectively meets the noise control standards.

References

[1] ZHANG Jianquan,HUANG Yunhua,LI Fu et al. Development of monorail transportation and its application in urban rail transit[J]. Railway Rolling Stock,2009,29(01):25-30.

[2] LI Fu,XU Wenchao,AN Qi. Development of suspended monorail vehicle and its current status[J]. Locomotive Electric Drive,2014(02):16-20+76.DOI:10.13890/j.issn.1000-128x.2014.02.003.
[3] GB/T 23431-2009, General technical conditions for articulated vehicles for urban light rail transit [S].
[4] Talotte C,Gautier P,Thompson D, et al. Identification, modelling and reduction potential of railway noise sources: a critical survey[J]. Journal of Sound and Vibration,2003,267(3).
[5] ZHAO Yanju, DENG Xiaojun, LIN Peng et al. Research on acoustic optimization of car body profile section structure of high-speed train[J]. Railway Rolling Stock,2017,37(01):40-42+71.
[6] ZHANG Li,ZHAO Weiheng,HE Chuan et al. Design and research on air conditioning system of suspended air railroad vehicle[J]. Railway Rolling Stock,2022,42(02):99-105.
[7] Li H , Thompson D , Squicciarini G ,et al.A framework to predict the airborne noise inside railway vehicles with application to rolling noise[J].Applied Acoustics, 2021, 179(3):108064.DOI:10.1016/j.apacoust.2021.108064.
[8] ISO 3381:2021 Railway applications - Acoustics - Noise measurement inside railbound vehicles.