Simulation Analysis on Noise Reduction Effect of Sound Barriers with Different Geometric Shapes for High-Speed Train

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Abstract. In order to study the noise reduction effect of different geometrical sound barriers on high-speed train aerodynamic noise, simulation studies were carried out on three shapes of sound barriers. The RNG k-epsilon turbulence model was used to calculate the aerodynamic drag of the high-speed train. Based on the large eddy simulation LES method and the FW-H acoustic analogy equation, the pulsating pressure of the train was extracted as the far-field noise source, and the noise reduction capabilities of the upright, semi-circular, and quarter-circular sound barriers were compared. The results show that the semi-circular sound barrier has the largest average insertion loss in far field, and its frequency response characteristics present the best match to the aerodynamic noise of high-speed train. Therefore, the semi-circular sound barrier has the best noise reduction effect.

1. Introduction

With the continuous innovation of high-speed railway technology, the running speed of trains has gradually increased, but the noise pollution generated by the operation of trains has become more and more serious. Therefore, the research on noise reduction of high-speed railway has become a hot research topic in recent years [1-2]. When high-speed railways run faster than 300km/h, aerodynamic noise will become the biggest source of noise from trains. The most widely used method to reduce the aerodynamic noise is to use sound barriers for noise treatment [3], and this method can effectively suppress the environmental impact of noise sources in the propagation path. Foreign research mainly starts with the propagation path and laws of sound waves, Paul Reiter et al. [4] simulated the noise reduction characteristics of three different internal structures sound barriers based on the finite element method, and established a mathematical model for the insertion loss of the sound barriers. Salomons et al. [5] studied the change of insertion loss of sound barriers and acoustic wave propagation path with air refraction, then completed numerical fitting. Wang Yanpeng et al. [6] studied the influence of sound barriers’ head structure on noise propagation by two-dimensional boundary element method, after that obtained the optimal structure and verified the results by designing experiments. While domestic research was aimed at noise reduction optimization of the noise barrier geometry. He Bin et al. [7] used the two-dimensional boundary element method to study the changes of the insertion loss of sound barriers in different head structures considering the multiple
reflections between ground, barriers and the vehicle body, then proved that the Y-type head sound barrier had the best acoustic effect. Wu Xiaoping et al. [8] used the finite element software ANSYS and the acoustic analysis software SYSNOISE to study the noise reduction effect of total height of sound barriers on the high-speed railway aerodynamic noise, and concluded that the suitable height of high-speed railway subgrade sound barriers should be 4-5m. Wang Jinrui et al. [9] studied the effect of changing geometries of the sound barrier head on the noise insertion loss at different positions based on the simulation results of Virtual Lab. The results showed that the T-type sound barrier was suitable for low-level noise reduction, while the Y-type sound barrier was more ideal for the reduction of high-level noise.

Above research mainly carried out acoustic research on the head structure and overall height of sound barriers to optimize the noise reduction, but did not involve the change of overall geometric shapes. Therefore, the influence of geometric shapes of sound barriers on the noise reduction is still unclear. In this paper, the RNG k-epsilon turbulence model was used to calculate the aerodynamic drag of high-speed trains. The large eddy simulation LES method and the FW-H acoustic analog equation were used in transient calculation to extract the pulsating pressure of the train as far-field noise sources, after which, the influence of overall geometric shapes of sound barriers on the far-field noise field was studied, which provided a reference for the further optimization of the noise reduction effect of sound barriers.

2. Mathematical Model
The speed of high-speed railway in this calculation was set to 350km/h (Mach number <0.3), which is a small relative sound velocity, so influences of the density change of the air can be ignored, and the air was regarded as an incompressible fluid. Based on this, the RNG k-epsilon two-equations model was used to calculate for steady state, and the calculation equations were as follows.

\[
\frac{\partial}{\partial t} (\rho k) + \frac{\partial}{\partial x_i} (\rho k u_i) = \frac{\partial}{\partial x_i} \left( \alpha_k \mu_{\text{eff}} \frac{\partial k}{\partial x_j} \right) + G_k + G_b - \rho \varepsilon - Y_M + S_k
\]  

(1)

\[
\frac{\partial}{\partial t} (\rho \varepsilon) + \frac{\partial}{\partial x_i} (\rho \varepsilon u_i) = \frac{\partial}{\partial x_i} \left( \alpha_k \mu_{\text{eff}} \frac{\partial \varepsilon}{\partial x_j} \right) + G_\varepsilon \frac{\varepsilon}{k} (G_k + C_{2\varepsilon} G_b) - C_{2\varepsilon} \rho \frac{\varepsilon^2}{k} - R_\varepsilon + S_\varepsilon
\]  

(2)

Where \(x_{i,j}\) was position coordinate, \(\rho\) was fluid density, and \(G_k\) was the turbulent flow energy produced by the average velocity gradient. Further, \(G_b\) was the turbulent flow energy generated by buoyancy, and \(Y_M\) was the contribution of volatility expansion to total dissipation rate. In addition, \(\alpha_k\) and \(\alpha_\varepsilon\) respectively meant inverse Prandtl coefficients of \(k\) and \(\varepsilon\). Finally, \(S_k\) and \(S_\varepsilon\) were custom active items.

The Smagorinsky-Lilly model in the Lilly LES large eddy simulation was used to complete the transient calculation, the influences of small-scale vortex in turbulent flow were ignored, and the turbulent motion of large-scale vortex was directly calculated, which can get the pulsating pressure on the train surface. The basic governing equations were as follows.

\[
\frac{\partial \rho}{\partial t} + \frac{\partial (\rho \bar{u}_i)}{\partial x_i} = 0
\]  

(3)

\[
\frac{\partial}{\partial t} (\rho \bar{u}_i) + \frac{\partial}{\partial x_j} \left( \rho \bar{u}_i \bar{u}_j \right) = - \frac{\partial P}{\partial x_i} + \frac{\partial}{\partial x_j} \left( \mu \frac{\partial \bar{u}_i}{\partial x_j} \right) - \frac{\partial \tau_{ij}}{\partial x_i}
\]  

(4)

Where \(\left\langle \right\rangle\) were filtered field variables, \(\rho\) was fluid density, and \(\bar{u}_{ij}\) meant filtered velocity component. Further, \(\mu\) was turbulent viscosity coefficient, and \(\tau_{ij} = \rho \bar{u}_i \bar{u}_j - \rho \bar{u}_i \bar{u}_j\), represented the influence of small-scale vortices on governing equations.
The source term of far-field noise is the coupling of quadrupole, dipole and monopole sources, where the quadrupole source is generated by Lighthill stress in the space near the train. The dipole source is distributed on the surface of the train, derived from surface pressure and viscous shear stress, and the monopole source is also distributed on the train surface, which is the result of volume pulsation caused by volume displacement. In this study the train was regarded as a rigid body, so there were no monopole sound sources, and because of the Mach number of the train speed was less than 0.3, the quadrupole sound source can also be neglected. Therefore, the source of far-field noise can be simplified to the dipole source of the train surface distribution. Based on this, the FW-H acoustic analogy equation was used to extract the vehicle body pulsation pressure for acoustic calculation to obtain the far field radiation noise sound pressure level. Solution to the simplified equation that ignored the quadrupole and monopole sources was as follows.

\[ p'(x,t) = -\frac{1}{2\pi\epsilon_0^2} \frac{\partial}{\partial t} \int \frac{x \cdot p_i(y,t')}{|x|^2 |1-M_0 \cdot x|} dS(y) \]  

(5)

Where \(x_i, y\) and \(p_i\) were sound point vector, sound source point vector, and air pulsation pressure on the surface of the car body, respectively. Finally, \(c_0\) was local sound speed.

Based on the above research results, the distribution characteristics of the far-field aerodynamic noise can be obtained by using the high-speed train surface pulsation pressure value obtained by equation (5).

3. Calculation model and parameters

3.1. High-speed train simulation model

The model was established for the CRH380A high-speed train. high-speed train during normal operation generally has 8 carriages, and total length of this train is more than 200m with a complicated shape, so this model needed to be simplified. Firstly, the surfaces of the train were treated as smooth surfaces, and the baffle below the front of the car, the connection part, the pantograph shroud were reserved. Due to the complicated geometrical structure of the bogie installation part, the calculation takes up too much computer resources. Besides, the detailed research on the aerodynamic noise characteristics of this part has been carried out [10], so the bogie installation location was simplified into a plane. Previous studies had shown that the air will tend to be stable after flowing through the front of the train because of the regular outer structure of the intermediate compartment, and the airflow of each car would be similar to each other, therefore the simulation model including a head carriage, a tail carriage and one middle compartment was built. The total length of the simulation train model was 78m, while the height was 3.7m, and the width was 3.38m, as shown in Fig. 1.

![Figure 1. Calculational model of high-speed train.](image)

A computational domain outside the train which can fully develop the wake flow was developed. Hybrid meshes were used, the 2m area near the high-speed train was divided with unstructured meshes, while the rest of the computational domain used structural meshes to increase the convergence speed. In order to improve the calculation accuracy, five prism layers were established on the surface of the high-speed rail to capture the transient changes of the pulsating pressure of the vehicle body, which was shown in Fig. 2.
3.2. Geometric shape and parameters of sound barrier

Geometric shapes of sound barriers can affect the propagation of high-speed rail aerodynamic noise. In order to study the noise reduction effect of the sound barriers with different geometric shapes, the upright, semi-circular and quarter-circular types were set up on the left and right sides of the high-speed train according to the standard of the roadbed plug-in metal sound barrier ((2009) 8225, 8325), just as Fig. 3 showed. The height of the 3 types of sound barriers were 3.05m from the ground, and their thickness were all 0.153m. As for the installation position of the sound barriers, the near-track side sound barrier was 4.75m away from the train center, and the far-track side was 9.75m. The length was 80m, 2m in front of the front of the train to 2m behind the rear of the train.

Figure 3. Schematic diagram of three different geometrical sound barriers: (a) upright sound barrier; (b) semi-circular sound barrier; (c) quarter-circular sound barrier.

3.3. Standard test points arrangement

The aerodynamic noise field of high-speed train is the radiated sound field of moving sound sources, so the radiation characteristics of dipole sources can be affected by various factors, such as the direction of movement of the dipole, the frequency of the pulsating pressure, and the Doppler effect between observers and high-speed trains, etc. To exclude the interference from non-studied items, as the Fig. 4 showed, a total of 9 far-field noise observation points were set at 10m intervals, 25m away from the center of the track and 3.5m from the ground according to the international noise measurement standard, the No. 1 measuring point corresponded to the front of the train, and the No. 9 measuring point corresponded to the rear end.

Figure 4. Sketch of Standard Test Points Arrangement.

4. Calculation results and analysis

4.1. Influence of geometric shape on noise reduction capability

Simulation of far-field aerodynamic noise was performed to study the difference in noise reduction capability of upright, semi-circular and quarter-circular sound barriers, under the condition of the speed of high-speed train was 350km/h. Sound barriers of different geometries have different effects on the scattering, diffraction and interference of sound waves during noise propagation. Besides, since the aerodynamic noise of high-speed trains is broadband noise and has a wide and irregular distribution in low frequency band and high frequency band, the distribution of far-field aerodynamic
noise with different geometrical sound barriers is inconsistent. The equivalent sound pressure level and insertion loss of no sound barrier, upright sound barrier, semi-circular sound barrier and quarter-circular sound barriers are shown in Fig. 5 and Fig. 6 respectively.

**Fig. 5. Equivalent sound pressure level.**

**Fig. 6. Insertion loss.**

Fig. 5 shows that the equivalent sound pressure level of high-speed train aerodynamic noise at nine standard measuring points first increases and then decreases when sound barrier is not added. The equivalent sound pressure level continues to increase from the No. 1 measuring point at the tip of train nose to the No. 4 measuring point near the pantograph shroud, while it has a gradually decreasing trend from the No. 4 measuring point to the No. 9 measuring point at the tip of the nose of the train tail. After sound barriers are added, this trend has not beed changed. The peak value of the equivalent sound pressure level still appears in the middle of the train. However adding sound barriers will cause the sound pressure level of the far-field aerodynamic noise to decrease, the lowest equivalent sound pressure level at all points appear after adding a semi-circular sound barrier, followed by an upright sound barrier. The minimum reduction in equivalent sound pressure level at the measurement points appear after a quarter-circular sound barrier is added, especially at the No. 1 measuring point corresponding to the tip of the train nose and the measuring points No. 7, 8, and 9 near the rear of the train, the value of the equivalent sound pressure level at those points has not been changed substantially.

Insertion loss is an important indicator for measuring the noise reduction of sound barriers. It refers to the difference of equivalent sound pressure level at sound receiving points between before and after the sound barriers are installed with constant external sound source and environment. The calculation formula for the insertion loss is as follows.

\[
IL = \Delta L_d - \Delta L_t - \Delta L_r - (\Delta L_s, \Delta L_G)_{\text{max}}
\]  

Where \(\Delta L_d\), \(\Delta L_t\), \(\Delta L_r\), \(\Delta L_s\), \(\Delta L_G\) are diffraction attenuation, transmission attenuation, reflected attenuation, obstacle attenuation, and ground absorption sound attenuation, respectively.

As shown in Fig. 6, semi-circular sound barrier holds the largest insertion loss at all points, which means it has the strongest noise reduction capability. Upright type sound barrier is second, and the quarter-circle type has the lowest noise reduction capability. Sound barriers with different geometrical shapes have different noise reduction capabilities for aerodynamic noise at different positions. Semi-circular sound barrier has a strong noise reduction capability for the far-field aerodynamic noise at positions near the front and the tail of the railway, the peak of the insertion loss appears at the No. 1 measuring point corresponding the tip of train nose at the front of the vehicle, which is 13.1dB. However, its ability to suppress the propagation of far-field aerodynamic noise will decrease in the middle of train, the lowest insertion loss appears at the 5th measuring point, which is 5.31dB. The
difference of insertion loss of the upright sound barrier at 9 standard points is not obvious. The peak value is 4.84dB, which appears at the 7th measuring point near the tail of the train, and the minimum value appears in the middle of the train corresponding measuring point 5, which is 2.14dB. The quarter-circular sound barrier has an obvious noise reduction capability at the No. 2 sounding point corresponding to the headline streamline position at the front of the train, its worst noise reduction capability appears near the front and the rear of the vehicle, all less than 1dB. In order to have a more direct comparison of the noise reduction capabilities of the sound barriers with three different geometries, the average insertion loss at nine points is averaged. The semi-circular sound barrier has the largest average insertion loss of 8.95dB, followed by the upright sound barrier of 3.63dB. The average insertion loss of the quarter- circular sound barrier is the smallest, 1.54dB.

4.2. Frequency response characteristics of sound barrier

In order to study the difference between the noise reduction capability of different shape sound barriers for different frequency bands, the No. 4 measuring point with the highest equivalent sound pressure level before adding sound barriers is set as the research object. Fig. 7, Fig. 8, and Fig. 9 show the spectrogram and the 1/3 octave spectrogram at the measuring point after adding upright sound barrier, semi-circular sound barrier and quarter-circular sound barrier respectively.

Fig. 7 shows that the sound pressure level of the far-field aerodynamic noise rises firstly and then decreases with the increase of frequency before adding sound barriers. The peak appears at about 500Hz, and the main energy of aerodynamic noise is concentrated in the low frequency band. After adding an upright sound barrier, the equivalent sound pressure level of each frequency band at the measuring point will decrease, and the frequency at which the peak appears will change from 500 Hz to 300 Hz. However, the sound pressure level at the measuring point after adding the upright sound barrier has no obvious difference with the frequency when the acoustic barrier is not added. It is proved that the upright sound barrier has similar absorption effect on the noise of each frequency band, and there is no significant difference in the suppression of noise propagation in low and high frequency bands.
Figure 8. Comparison of the spectrum and the 1/3 octave spectrum of upright sound barrier and no sound barrier.

It can be observed in Fig. 8 that after adding the semi-circular sound barrier, the sound pressure level at the measuring point tends to be gentle, and the peak appears near 500 Hz, which is the same as the value without sound barrier. However, with the increase of frequency, the sound pressure level of aerodynamic noise does not decrease, but tends to be close to a straight line, and there is an increasing trend appears in the high frequency band above 4000 Hz. These phenomena are significantly different from the law of change in sound pressure levels when no sound barrier is added. The above results show that the semicircular sound barrier has good noise reduction ability for low frequency noise. As the frequency increases, the noise reduction capability of the semi-circular sound barrier will gradually weaken, but its acoustic performance is still better than the upright sound barrier in high frequency band.

Figure 9. Comparison of the spectrum and the 1/3 octave spectrum of quarter-circular sound barrier and no sound barrier.

The changes after adding a quarter-circular sound barrier are presented in Fig. 9. The results show that the quarter-circular sound barrier has relatively obvious suppression ability for aerodynamic noise below 1000 Hz. However, there is no obvious noise reduction capability for medium frequency noise and high frequency noise above 2000 Hz. Its comprehensive acoustic performance is the worst.

In summary, since the aerodynamic noise energy of high-speed trains is mainly concentrated in the low frequency band, which matches with the sound absorption characteristics of the semi-circular...
sound barrier. Besides, the average insertion loss of the semi-circular sound barrier is also the largest. Therefore, using the semi-circular sound barrier can achieve the most significant noise reduction effect.

5. Conclusion
The noise reduction effect of the upright, semi-circular and quarter-circular sound barriers was simulated and analyzed. The conclusions drawn from the obtained results are as follows.

1) The aerodynamic noise of high-speed trains is broadband noise. When the sound barrier is not added, the distribution of far-field aerodynamic noise increases first and then decreases from the front to the rear. The addition of sound barriers of different geometries does not change this trend, but it will result in a decrease of the equivalent sound pressure level. The range of reduction from large to small is a semi-circular sound barrier, an upright sound barrier, and a quarter-circle sound barrier.

2) The insertion loss distributions of the three geometrical sound barriers at the standard measuring points are different from each other. The peak value of the semi-circular sound barrier insertion loss appears near the front and the rear of the vehicle. The insertion loss corresponding to the middle part of the vehicle body is significantly lower than that at both ends. There is no obvious difference in the insertion loss of the upright sound barrier in different positions of the body, but it still shows a trend of high and low at both ends. The insertion loss of the quarter-circular sound barrier is maximized in the streamlined part of the front, constant in the middle, and lowest in the vicinity of the rear of the train. In order to be able to have a more direct comparison of the noise reduction capabilities of the sound barriers with three different geometries, the average of the insertion losses is obtained, in order from big to small is the semi-circular sound barrier, the upright sound barrier, and the quarter-circle sound barrier.

3) The upright sound barrier has no significant difference in the noise reduction capability of the aerodynamic noise in different frequency bands, and the noise reduction capability of the semi-circular sound barrier decreases with the increasing frequency, but its acoustic performance is still superior to the upright sound barrier. The noise reduction capability of the quarter-circular sound barrier is not obvious in the high frequency band. In summary, the semi-circular sound barrier has the strongest noise reduction capability and has the best match for the aerodynamic noise of high-speed trains.

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