Research Article

An Experimental Investigation into the Difference in the External Noise Behavior of a High-Speed Train between Viaduct and Embankment Sections

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Received 1 September 2020; Revised 26 November 2021; Accepted 3 March 2022; Published 29 March 2022

Academic Editor: Arcanjo Lenzi

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Track construction is likely to exert a significant effect on railway environmental noise. In this study, a detailed comparative investigation was conducted to analyze the differences in the external noises generated by a Chinese high-speed train passing through typical lines at different speeds. Acoustic experiments were conducted on both viaduct and embankment sections by using a microphone array having 78 channels, to distinguish the effects of two types of track structures on the sound fields around these, identify the sources, and determine the contribution and distribution of each part of the train. The quantized sound power contribution of each region on the train surface determined using the identification results obtained from the experiments and analysis shows that the main noise sources of the train are located in three regions: the lower parts, bogie, and train body. The pantograph was the dominant noise source at speeds above 300 km/h. Considering the embankment as a reflective surface compared with the viaduct, the ground reflection effect results in a higher sound power level in the embankment section. Furthermore, the largest difference between the two sections increases to 1.8 dB at a speed of 350 km/h. In addition, the reflection effect is more apparent at high speeds, and the reflection is evident in the low-frequency band (< 1000 Hz). The analysis of the experimental results is effective for identifying the difference and satisfies the requirement for reducing external pass-by noise in typical operational lines.

1. Introduction

The development of high-speed trains has resulted in various problems [1–4]. The external noise generated is becoming a severe issue for individuals residing near rail lines. In addition, external noise is an important index for evaluating the advancement of high-speed trains. The train noise problem has drawn significant attention from numerous researchers [5, 6]. They have attempted to understand the sources and mechanisms that generate external noise for both viaduct and embankment sections with the aim of controlling and reducing the overlaid noise. Till the present, research has been conducted experimentally, through model prediction, or using a combination of these two approaches.

An important aspect is the identification of noise sources in a moving train. It has been investigated experimentally using microphone array techniques. In the 1970s, array measurement combined with the beamforming method was introduced to the study of acoustics signal processing [7]. Here, a linear array is applied to study the aerodynamic noise source of jets [8]. In the same period, beamforming with a microphone array was also applied to trains to form an acoustic map to identify noise sources. King III and Bechert were the first to introduce a linear array with 14 microphones to identify the noise source in a high-speed train at a maximum speed of 250 km/h [9]. Barsikow and King III studied the problems in eliminating the Doppler effect and analyzed the noise characteristics of a train based on the test results [10]. Since then, significant progress has been
achieved with beamforming in the noise source location for enhancing data acquisition and operational capabilities [11]. Microphone arrays are typically applied in combination with the beamforming method to quantify the noise sources and individual contributions of a pass-by high-speed train [12]. For example, Dittrich et al. [13] introduced a T-like array, and Schulte-Schulte-Werning et al. [14] developed a spiral-like array to identify train noise sources. The noise sources of ICE trains within a wide frequency range (200–3150 Hz) have been identified for reducing railway noise. These previous studies demonstrated the potential of microphone array techniques for identifying train noise sources.

A previous study on noise source identification determined that at speeds ranging from 20 to 100 km/h, the wheel-rail noise dominates the overall noise and is approximately 5.0–10.0 dB(A) higher than the noise generated by other sources [15]. Source identification for an IC2000 train traveling at a speed of 190 km/h was investigated by Thron [16]. He showed that the bogie noise dominated below 2000 Hz and that sounds with frequencies above 4000 Hz originated along the entire train height.

Noise is an important factor in determining high-speed train operation. The distribution of external noise composition for TGV trains was studied by Mellet et al. [17]. Experiments to identify noise sources were conducted for other TGV trains as well, and the results indicated that the first bogie and pantograph dominated as the speed increased [18].

In addition, Koh et al. identified the noise source in Korean high-speed trains at a maximum speed of 300 km/h on a ballast track in the embankment section [19]. Here, the noise distribution along the train height was analyzed in the frequency range of 2500–4500 Hz. They identified traction noise, rolling noise, and aerodynamic noise as the main noise sources, as is generally acknowledged [20].

The results of noise source identification experiments conducted on the Japanese Shinkansen high-speed trains using a spiral microphone array indicated that the noise generated by wheels was dominant at 340 km/h on a non-ballast track in the embankment section [21]. Noh et al. [22, 23] conducted another series of experiments on Korean high-speed trains traveling at 390 km/h on a ballast track in an embankment section. It was observed that the intercoach spacing, wheels, and pantograph were the dominant sources of external noise. He [24] conducted a comprehensive experiment on the noise sources of a Chinese high-speed train in the vertical direction at a maximum speed of 390 km/h in the viaduct section.

Microphone array measurements were performed under different conditions (vehicles and tracks) in Europe, Japan, Korea, and China. Although considerable information has been obtained from these measurements, a few questions remain unanswered. For example, the difference in external noise behavior between the viaduct and embankment sections has not been investigated.

Furthermore, several studies have been conducted to model and predict high-speed train rolling and aerodynamic noises. For example, Zhang et al. [25] developed a sound radiation model for ballast tracks. Han et al. [26] developed a numerical model for wheel-rail noise analysis. This was achieved considering the effect of flexible wheelsets and a prediction method for transient wheel-rail noise. Sheng et al. [27] presented modified equations for sound radiation prediction from an infinitely long periodic slab track by using an extended Fourier transform method. Zhang et al. [28] investigated the contribution of different noise sources through experiments and simulations and analyzed different control noise sources. Zhang et al. [29] introduced a novel type of semiclosed noise barrier (SCNB). It performed better than the existing noise barrier in reducing external noise.

These previous studies extended the knowledge base on noise generation mechanisms, evaluated the source intensity and directivity, and attempted to reduce the noise generated from different sources. Most of these studies considered ballast or nonballast track conditions. However, the differences among advanced operational high-speed railways, particularly in the viaduct and embankment sections, were not considered. This is particularly so for China. Different railways significantly influence external noise and its characteristics. In this study, the necessity of the main differences in Chinese high-speed railways was identified and discussed.

The difference in external noise behavior of a high-speed train between the viaduct and embankment sections was investigated based on the microphone array measurement data. In Section 2, the dedopplerization in the beamforming method and the fundamental principle of the deconvolution method (Fourier-based nonnegative least-squares (FFT-NLSS)) are introduced briefly in conjunction with the experimental setup. In addition, the reflective coefficient related to the embankment section is estimated. In Section 3, the noise data measured using the microphone array for a typical Chinese high-speed train running at different speeds are analyzed. Furthermore, the characteristics of various noise sources in the embankment and viaduct sections are discussed. The main differences in the results and analyses of the embankment effect are presented in Section 4. The paper is concluded in Section 5.

2. Method of External Noise Source Identification and Consideration of Ground Surface

When a train travels at speed above 350 km/h on a rail line, the Doppler effect on the sound pressure measured at fixed positions near the track is significant. As a result, the direct use of these measured sound signals significantly reduces the identification accuracy. Advanced microphone array techniques have features that can effectively eliminate the Doppler effect. The principles underlying these features are introduced briefly in Section 2.1. The microphone array used and the measurement setup are described in Section 2.2. In the embankment section, the train is close to the ground surface. This may play a significant role in sound generation and its propagation by reflection and absorption. The reflection coefficients of the ground surface are introduced in Section 2.3. These are used to analyze the difference in
external noise behavior of the train between the viaduct and embankment sections.

2.1. Beamforming, Dedopplerization, and Quantification Approach. Acoustic beamforming can be used on far-field measurements. An array produces a spatial sampling of a sound field, whereas a beamforming algorithm performs a spatial filtering operation that enables one to map the distribution of the sources at a certain distance from the array and thereby locate the strongest sources. The output power spectrum of classical beamforming is expressed as follows [11]:

$$\text{BF}(\chi^p, \omega_k) = \frac{1}{N} \sum_{m=1}^{N} u_m A_m(\chi^p, \chi^m) P_m(\omega_k) e^{j\omega \chi^p - \chi^m} \chi^p - \chi^m |c|;$$

where $P_m(\omega_k)$ is the pressure signal at the $m$-th microphone and at the angular frequency $\omega_k$; $u_m$ is a weighting factor or shading coefficient applied to the $m$-th microphone; $A_m(\chi^p, \chi^m)$ is a scaling factor that can also consider amplitude reduction, $A_m(\chi^p, \chi^m) = 4\pi \| \chi^p - \chi^m \|$. Each location of a grid of $N$ points (control points), $p = 1, \ldots, N$, in which a set of candidate sources (usually monopoles) can be virtually placed, and a discrete set of $M$ microphones that sample the sound field and are each located at $\chi^m$, $m = 1, \ldots, M$. And $c$ is the wave propagation speed in the medium.

Equation (1) can be reformulated using the vector matrix notation:

$$\text{BF}(\chi^p, \omega_k) = \mathbf{g}^H \mathbf{Wp}. \quad (2)$$

The term $\mathbf{g}$ in equation (2) is commonly called the steering vector because it contains phasors whose exponents cancel the wave propagation-related phase shifts. It is common to include $A_m$ in the steering vector notation. $\mathbf{p}$ is a vector whose elements are the complex pressures $P_m(\omega_k)$ measured at each microphone location, whereas $\mathbf{W}$ is a diagonal matrix whose elements are the weighting factors. The superscript $\dagger$ represents the complex conjugate transpose operator.

In the process of identifying a sound source when relative motion occurs between the noise source and measurement array, the collected sound signal displays the Doppler effect. The conventional beamforming technology cannot accurately identify the sound source location and characteristics in the presence of a strong Doppler effect. Therefore, dedopplerization is an essential procedure.

According to the Morse moving source theory [30], when the Mach number of a moving source $M$ is less than one,

$$p_{r0}(t) = \frac{q'(t - R(t)/c) \cos \theta - MV}{4\pi R(t)(1 - M \cos \theta)^2} + \frac{q(t - R(t)/c) \cos \theta - M V}{4\pi R(t)\lambda^3(1 - M \cos \theta)^3},$$

where $q(t) = q_0 e^{j\omega_0 t}$ denotes the intensity of the source, $q_0$ denotes the amplitude of the sound intensity, $\omega_0$ denotes the angular frequency of the source noise, and $q'(t)$ denotes the derivative of the mass flow of the source. In addition, $R(t)$ is the distance between the source and receiver points (microphone), and $\theta$ is the angle between the line connecting the source and microphone and the line of motion of the source.

When $R(t)$ is in the far-field, the second term in equation (3) can be omitted:

$$p_{r0}(t) = \frac{q'(t - R(t)/c)}{4\pi R(t)(1 - M \cos \theta)^2}. \quad (4)$$

When $M = 0$, equation (4) can be expressed as follows:

$$p_{r0}(t) = \frac{q'(t - R/c)}{4\pi} r = \frac{j\omega_0 q_0 e^{j(\omega_0 t - \kappa r)}}{4\pi}. \quad (5)$$

Considering discrete sampling, $p(t)$ is the sound pressure measured using a microphone at time $t$, and $q'(t - R(t)/c)$ can be calculated from each $p(t)$. Note that $R(t)$ is no longer equally sampled. Therefore, time interpolation should be applied to $q'(t - R(t)/c)$. After interpolation at time $t_i$, $q'(t_i)$ can be obtained. It has equally sampled values. Substituting $q'(t_i)$ into equations (4) and (5), the sound pressure measured by each microphone can be calculated by eliminating the Doppler effect as follows:

$$p_{r0}(t) = \frac{1}{t} p_{r0}(t) R(t)(1 - M \cos \theta)^2 e^{j(\omega_0 R(t) - \kappa r)}. \quad (6)$$

In the far-field condition, the distance between the microphone and sound source is sufficiently large ($>2DL^2$; $D$ is the max diameter of the array, and $\lambda$ is the acoustic wavelength). The signal data with the Doppler effect collected by the microphone can be corrected if the relative position between the sound source and microphone and the motion speed of the sound source at that time are known.

Recent research on high-speed trains has widely adopted the acoustic beamforming method using a microphone array. It is considered to be effective for obtaining highly directional beam characteristics [31]. The quantification approach adopted in this study is based on a deconvolution method called FFT-NNLS. Here, the matrix multiplications of the NNLS method are replaced by a spectral procedure [32–34]. This method has the advantages of high analysis speed and side-lobe elimination. The solution for $q^{(n+1)}$ can then be obtained as follows:

$$q^{(n+1)}(r') = \max(q^{(n)}(r') + \lambda \omega^n(r'), 0). \quad (7)$$

where $q$ is the unknown source distribution column vector (all its elements are at least zero), $r'$ indicates the source location, $\omega^n$ is the search path via the present position of $q^{(n)}$, and $\lambda$ is the optimal step. The result obtained using the spatial Fourier transform can be expressed as follows:

$$\omega^{(n)} = -r^{(n)} \ast \text{PSF} = -F^{-1} \left[ F^{*} F \right] r^{(n)} \ast \text{PSF} \right] \right], \quad (8)$$

where $r^{(n)}$ is the residual vector, PSF is the point spread function of the representative source, $F$ denotes a forward Fourier transform, and $F^{-1}$ denotes the corresponding inverse transform. Substituting equations (8) into (7), when the number of times $n$ is sufficiently large (e.g., 100), the
result of “q” imaging is similar to that of the actual sound source. This significantly improves the resolution of sound source identification. Classic noise source identification for different high-speed trains (TGV, Shinkansen, KTX, and CRH) using the beamforming method are shown in Figure 1. It can be observed that the identified sources are mainly in the bogie region, rising pantograph, intercoach gap, and other protruding structures such as access doors, front noise, and windscreens. The identification accuracy has improved with continuing research, and the knowledge on the external noise of high-speed trains has been enriched. Moreover, to meet the development of “eight vertical and eight horizontal high-speed railway network” in China, a better understanding and demand of high-speed train running in different lines is needed to be achieved.

2.2. Description of the Microphone used and the Measurement Setup

2.2.1. Used Microphone Array. Figure 2 presents the arrangement of the microphone array (B&K WA-0890-F). It comprises 13 spokes and 78 microphones with a diameter of 4.0 m. The array opening angle is 70°. The 1/3-octave central-band frequencies range from 200 to 4000 Hz, which is adequate for identifying the principal aeroacoustic and rolling noise sources [17]. Figure 3 shows dynamic ranges from 200 to 4000 Hz. The main lobe-to-side lobe ratio (MSR) is all above 30 dB. This indicates the suitability of the characteristics for source identification and anti-interference performance.

The software module B&K NSI array acoustic post-processing was applied to the exterior noise source identification output. The sound power was then obtained by integrating the sound intensity over each area [12]. Each contribution is calculated using the following:

\[ C_s = \int \Delta S I(S) dS / \int S I(S) dS \]  (9)

where \( I(S) \) is the sound intensity at a discrete point, \( \Delta S \) is the area of each zone, and \( S \) is the total area of all the zones.

\[ Z_s = \rho c = (\rho_0 c_0) \tilde{\rho}_c, \]  (11)

\[ \tilde{\rho} = \left\{ \alpha_1 \left( \frac{\rho_0 f}{\sigma} \right)^{-\alpha_2} + i \left[ 1 + \alpha_3 \left( \frac{\rho_0 f}{\sigma} \right)^{-\alpha_4} \right] \right\} \ast \left\{ \alpha_2 \left( \frac{\rho_0 f}{\sigma} \right)^{-\alpha_5} + i \left[ 1 + \alpha_3 \left( \frac{\rho_0 f}{\sigma} \right)^{-\alpha_6} \right] \right\}, \]  (12)

\[ \tilde{\alpha} = \frac{1 + \alpha_3 (\rho_0 f / \sigma)^{-\alpha_2} - 2 \alpha_4 (\rho_0 f / \sigma)^{-\alpha_3}}{2 \alpha_3 (\rho_0 f / \sigma)^{\alpha_4} + \alpha_3 (\rho_0 f / \sigma)^{-\alpha_5} + \alpha_3 (\rho_0 f / \sigma)^{-\alpha_6}}. \]  (13)

where \( \rho_0 \) is the density of air, \( c_0 \) is the speed of sound waves in air, and \( f \) is the frequency. \( \sigma \) is the flow resistivity and has a value of approximately 5000 N/m² for the site soil. \( \alpha_1 - \alpha_6 \) are the measured empirical constants and are listed in Table 1.

2.2.2. Measurement Setup. The microphone array measurements were performed for two railway sections: viaduct and embankment. These have an identical track form: a nonballasted slab track. Because the railway is newly opened and the two sections are placed relatively close to each other, the track and soil in these sections can be assumed to be highly similar and under suitable conditions. In the measurement, the array was installed at a horizontal distance of 7.5 m from the centerline of the track, and the array center was 1.8 m above the rail top surface (Figure 3). A photoelectric sensor was used to capture the speed of the train. In addition to the array, three microphones were positioned at P1 (7.5 m, 1.2 m), P2 (7.5 m, 3.5 m), and P3 (25 m, 3.5 m) to measure the train pass-by noise. This is as per ISO standard 3095:2013 [35]. The train comprises eight carriages and has a length of 212 m. The second, fourth, fifth, and seventh carriages are motor cars, and the remaining are trailer cars.

2.3. Reflection of Sound Waves by Ground Surface in the Embankment Section. Sijtsma and Holthuysen [36] demonstrated that the array measurement results deviate significantly from the free-field result when the source is excessively close to a reflection surface. When a train runs along a track at grade, the ground surface can absorb and reflect sound. This absorption and reflection can affect the array measurement results because both train and array are close to the ground surface in the embankment section. For a plane wave impinging on the ground surface, the reflection coefficient of the ground surface (\( \alpha \)) is defined as the ratio of \( |\mathbf{P}_r| \) to \( |\mathbf{P}_i| \) [37]:

\[ a = \frac{|\mathbf{P}_r|}{|\mathbf{P}_i|} = \frac{Z_s \cos \gamma - \rho_0 c_0}{Z_s \cos \gamma + \rho_0 c_0} \]  (10)

where \( \mathbf{P}_i \) and \( \mathbf{P}_r \) are the amplitudes of the incident and reflected sound waves, respectively, and \( \gamma \) is the angle of incidence of the sound waves. \( Z_s \) is the acoustic impedance of the ground surface and can be expressed as [37, 38]
(a)

(b)

(c)

Figure 1: Continued.
reflection at low frequencies from the ground surface may affect the frequency spectrum and the value of the external noise. This is discussed below.

3. Differences in External Noise Behavior of Train between Viaduct and Embankment Sections

This section describes the investigation of the differences in external noise behavior of train between the viaduct and embankment sections. For this purpose, the noise sources of the train were divided according to the region for identification and quantification (in Section 3.1). A comparison between the viaduct and embankment sections was performed for the entire train in terms of the noise from individual source regions. The sound intensity maps of the entire train at different speeds are presented in Section 3.2. It provides an overview of the high-speed train. The overall differences for the entire train are discussed in Section 3.3. The differences in the spectrum of the entire train are examined in Section 3.4, and those in the individual source regions are examined in Section 3.5.

3.1. Definition of Noise Source Regions for the High-Speed Train

Inverse methods address the problem for all sources simultaneously. That is, these attempt to determine the best source distribution that can optimally approximate the pressure distribution at the microphone location. Because source interference is thereby potentially considered, inverse methods can address correlated/uncorrelated and sparse/spatially distributed sources [11]. Different colors representing different intensities of sources correspond to the original figure. Then, the acoustic map is drawn.

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**Figure 1:** Classic noise source identification for different types of high-speed trains [17, 21, 22, 24]. (a) Noise source identification for TGV high-speed train (2006) [17]. (b) Noise source identification for Shinkansen high-speed train (2008) [21]. (c) Noise source identification for KTX high-speed train (2013) [22]. (d) Noise source identification for CRH high-speed train (2014) [24].

**Figure 2:** Microphone positions of array.

**Figure 3:** The dynamic ranges of the used array in frequency domain.
3.2. Difference in Distribution of the Entire Train at Different Speeds. Because the array can extend beneath the railhead, further calculations and data analysis of the reflection were performed. The calculated area extends 0.5 m beneath the railhead (which is the most apparent reflection region). Figure 6 shows the distribution of the noise sources in terms of the sound intensity of the train within the speed range of 160–350 km/h in both viaduct and embankment sections, as obtained by B&K NSI array acoustic postprocessing. The main external noise sources are presented in this figure. It is observed that bogies (particularly the leading ones) are the main noise sources. Turbulences around the bogies and rail vibrations cause the region under the train floor to be noisier than those in the other parts of the train. The motor bogies in the second carriage are noisier than the trailer bogies in the other cars under 200 km/h. This is owing to the traction motors. With increasing speed, the first bogie of the first carriage becomes more evident because of the increasing aerodynamic noise [39]. When the operational speed exceeds 300 km/h, the lifted pantograph becomes the dominant noise source.

The noise maps shown in Figure 6 indicate the differences in noise between the viaduct and embankment sections. The region beneath the rail is evident in the embankment section. However, it is difficult to characterize and quantify the differences only by examining these maps. Therefore, alternative approaches for analyzing the differences must be developed. This is discussed below.

3.3. Difference in Overall Sound Power Level of the Entire Train and Passby Noise. The sound intensity (achieved in the B&K NSI array acoustic postprocessing) can be calculated for each grid on the source plane for each frequency. The total sound power of the train at a frequency is obtained by integrating the sound intensities at that frequency over the entire source plane. The total sound power at different frequencies is added to obtain the overall sound power level of the entire train. The average overall sound power levels at different speeds are shown in Figure 7. Here, the overall sound power level of the train when it runs in the embankment section is higher than that when it runs in the viaduct section at an identical speed. Furthermore, this difference increases with the train speed: 0.8 dB, 1.2 dB, 1.3 dB, 1.6 dB, and 1.8 dB at 160, 200, 250, 300, and 350 km/h, respectively.

Figure 7 shows that the train is noisier when it runs in the embankment section than when it does in the viaduct section. The difference increases with the train speed. Because the train runs on the same newly constructed railway line, the track slabs and the wheel-rail roughness in these two sections are similar. Thus, for a given train speed, the difference in noise is caused only by the difference in track form. The embankment section can cause significantly more sound diffraction than the viaduct section, particularly at low frequencies. The differences in the frequency domain are presented in the next section.

3.4. Difference in the Spectrum of Overall Sound Power Level of the Entire Train. The spectra of the train when it runs in the viaduct and embankment sections at different speeds are shown in Figure 8. Here, a square is drawn within the significant frequency bands (the noise levels within these are at least equal to 10 dB less than the maximum). The frequency range widened significantly as the train speed increased. In particular, each spectrum peaked at 630 Hz in both viaduct and embankment sections. This feature requires further investigation.

The acoustic behavior in the embankment section was similar to that observed in the viaduct section for frequencies above 630 Hz. However, at lower frequencies, the difference in behavior increased at a speed of 250 km/h. When the train speed exceeded 300 km/h, the embankment section was noisier than the viaduct section in each frequency band.

**Table 1: Values of reflection coefficients [38].**

| $\alpha_1$ | $\alpha_2$ | $\alpha_3$ | $\alpha_4$ | $\alpha_5$ | $\alpha_6$ | $\alpha_7$ | $\alpha_8$ |
|------------|------------|------------|------------|------------|------------|------------|------------|
| 0.189      | 0.595      | 0.089      | 0.700      | 0.057      | 0.754      | 0.087      | 0.732      |

**Figure 4:** Reflection coefficient in the frequency range of site soil in the embankment.

**Figure 5:** The division of the analysis region to more accurately distinguish the amplitude and characteristics of the external noise generated by each source (four carriages of the train set are shown for the symmetrical structure). Each train region has an evident difference in noise formation: the lower parts involve auxiliary noise and aerodynamic noise; the bogie region mainly involves the rail-wheel noise; and the body region, roof region, and pantograph mainly involve the aerodynamic noise.
Table 2: Definitions of noise source regions of the train.

| No. | Region      | Vertical direction (m) | Longitudinal direction (m) |
|-----|-------------|------------------------|---------------------------|
| 1   | Lower parts | 0                      | 1.5                       | 0                         | 212                        |
| 2   | Body        | 1.5                    | 4.0                       | 3                         | 212                        |
| 3   | Roof        | 4.0                    | 4.2                       | 6.0                       | 206                        |
| 4   | Pantograph  | 3.7                    | 6.0                       | 3.0 m before the maximum sound intensity point | 3.0 m after the maximum sound intensity point |
| 5   | Bogie       | 0                      | 1.5                       | 2.5 m from the bogie center to the front and back |

Figure 5: Division of the train into regions.

Figure 6: Continued.
The difference in the external noise between these two sections is more apparent in the low-frequency bands, particularly below 1000 Hz. As discussed above, the reflection of sound waves contributes considerably to the low-frequency band. The difference in each frequency band increases with the train speed, particularly above 300 km/h. This is attributed to the larger difference between the two sections. Another significant difference between peaks was observed at 250 Hz, which may be attributed to the reflection effect. Moreover, a higher speed causes more evident reflection.

3.5. Difference in Overall Sound Power Level of Individual Source Region

3.5.1. Contribution of Each Source Region to the Overall Sound Power. The sound power level of each region was obtained from the software output. The contribution percentage is the ratio of the sound power level of each region to that of the entire train (represented as a percentage). The contributions of each source region (as defined in Section 3.1) of the train at different speeds are shown in Figure 9. In both the measurement sections, the lower parts account for...
Figure 7: Sound power level of all acoustic image regions at different speeds in the viaduct and embankment sections.

Figure 8: Continued.
the largest amount (>90%) of noise radiation energy. These are followed by the body, pantograph, and roof regions. The noise in the bogie region accounts for the majority (60%) of the overall sound power, and the proportion of the overall sound power does not vary significantly with train speed. More specifically, in the viaduct section, with an increase in speed from 160 to 350 km/h, the sound power proportion in the lower parts decreases from 93.81% to 79.20%, and that of the bogie region varies marginally from 58.44% to 53.75%. In the embankment section, the sound power proportion of the lower parts decreases from 85.91% to 70.75%, whereas that of the bogie region varies from 46.90% to 47.54% as the speed increases. The proportion of the lower parts tends to decrease with speed and those of the pantograph and body regions increases accordingly. This was because these two regions generate noise mainly aerodynamically. Because the bogie is one of the lower parts, the marginal variation in the proportion of the bogie noise indicates that the aerodynamic noise in the bogie also increases with speed.

3.5.2. Difference in Noise of a Source Region between Embankment and Viaduct Sections. The contribution of the lower parts (particularly the bogie) is the largest. The differences in sound power levels of these regions between the embankment and viaduct sections for each speed are shown in Figure 10(a). The difference for the lower parts increases with speed. The bogie region emits complex low-frequency noise and low-frequency reflections. The aerodynamic characteristics of the body region are significant in the high-

Figure 8: Spectrum of the sound power level of the train running in the viaduct and embankment sections at different speeds. (a) Sound power level spectrum at 160 km/h. (b) Sound power level spectrum at 200 km/h. (c) Sound power level spectrum at 250 km/h. (d) Sound power level spectrum at 300 km/h. (e) Sound power level spectrum at 350 km/h.
The train body mainly generates high-frequency aerodynamic noise, and the embankment for the high-frequency reflection effect is marginal. The differences between the roof, body, and pantograph are not regular because the reflection from these regions in Figure 10(b) is not evident. The differences in the sound powers of the bogie and lower parts evidently vary with increasing speed, whereas those in the pantograph, roof, and body regions are less apparent. This indicates that the reflection effect is more prominent in near-ground space. With increasing space, the sound waves spread outward, which reduces the reflection effect.
Figure 11: Continued.
In the pass-by noise through the entire train, the wheel-rail rolling noise contributes more than the aerodynamic noise. Because the lower region, particularly the bogie, is the dominant noise source, the noise occurring in this region should be reduced and suppressed first. The absorbing panels’ installation on bogie skirts has the effect of reducing the noise around the bogie [1], and a damper can be installed to restrain the vibration of the wheels and rails [40, 41]. Noise barriers are also set up to alter the path of noise transmission.

The average pass-by sound pressure level measured at P3 (Figure 11, ISO3095:2013 [35]) is shown in Figure 12. The differences are evident at each speed and increase with the speed. This agrees with the reflection effect explained above.

**4. Comparison of Noise-Train-Speed Dependence between the Embankment and Viaduct Sections**

All the test results indicate a variation in the noise behavior with speed. These also show the acoustic characteristics of the high-speed train. The law of variation in radiating noise with speed in typical regions of the train is obtained using an unknown constant determined by the linear regression curves. This is shown in Table 3.

Table 3 presents the linear fitting results for the entire train, lower parts, and bogie. Here, \( V_0 \) is a relatively low speed (e.g., 160 km/h), \( L_0 \) is the sound power level at \( V_0 \), and the regression coefficient \( \beta \) differs for each speed. In both the sections, \( \beta \) exhibits an inflection point at 250 km/h. This indicates that aerodynamic noise gradually becomes the dominant source outside the train. The ground reflection effect in the embankment section is particularly evident above 250 km/h. The regression coefficients of the pantograph in the viaduct and embankment sections are 52.53 and 51.45, respectively, which are close to the aerodynamic noise growth coefficient 60. This indicates that the pantograph noise is dominated by the aerodynamic noise in the entire speed range.

Figure 13 shows the test results of the linear fitting relationships between the overall noise, noise in the lower parts, noise in the bogie region, and pantograph noise.
Table 3: Linear fitting results of radiating sound power level in typical regions.

| Region       | Operational section | Speed range (km/h) | $\beta$ | $L_o$ | $R^2$ |
|--------------|---------------------|--------------------|---------|-------|-------|
| Entire train | Viaduct             | $160 \leq V \leq 250$ | 19.68   | 124.97| 0.97  |
|              |                     | $250 \leq V \leq 350$ | 34.42   | 120.83| 0.98  |
|              | Embankment          | $160 \leq V \leq 250$ | 20.85   | 125.44| 0.94  |
|              |                     | $250 \leq V \leq 350$ | 35.68   | 121.78| 0.98  |
| Lower        | Viaduct             | $160 \leq V \leq 250$ | 18.66   | 124.46| 0.98  |
|              |                     | $250 \leq V \leq 350$ | 31.15   | 121.66| 0.95  |
|              | Embankment          | $160 \leq V \leq 250$ | 19.42   | 124.71| 0.93  |
|              |                     | $250 \leq V \leq 350$ | 32.35   | 121.93| 0.92  |
| Bogie        | Viaduct             | $160 \leq V \leq 250$ | 17.82   | 121.59| 0.94  |
|              |                     | $250 \leq V \leq 350$ | 31.52   | 117.49| 0.94  |
|              | Embankment          | $160 \leq V \leq 250$ | 18.73   | 121.73| 0.96  |
|              |                     | $250 \leq V \leq 350$ | 33.67   | 117.97| 0.92  |
| Pantograph   | Viaduct             | $160 \leq V \leq 350$ | 52.53   | 103.11| 0.95  |
|              | Embankment          | $160 \leq V \leq 350$ | 51.45   | 104.12| 0.95  |

(a) Figure 13: Continued.
Figure 13: Continued.
with increasing speed in both viaduct and embankment sections.

These figures clearly indicate the inflection point. It reveals that at 250 km/h, the aerodynamic noise in the entire vehicle begins to contribute more significantly to the pass-by noise. The regression coefficient in the pantograph region is close to 60. This also indicates that the noise component of the pantograph is essentially aerodynamic noise as a dipole sound source. Owing to the high vertical position of the pantograph, its noise was negligibly affected by the line form. The linear regression curve can be used at a higher train speed. However, the aerodynamic noise from the bogie and pantograph should be controlled, particularly in the embankment sections.

5. Conclusions

This study experimentally investigates the differences in the external noise behavior of a Chinese high-speed train between the viaduct and embankment sections. The following conclusions can be drawn:

(1) The application of using the array is an effective way to achieve the noise character of a moving high-speed train. The overall radiating sound power level in the embankment section is 1.8 dB higher than that in the viaduct section at 350 km/h. This is mainly due to the reflection of the sound waves from the terrain.

(2) In both sections, the lower parts contribute the most to the total radiated sound power (93.81%−70.75%), followed by the body region (4.69%−24.25%) and pantograph region (0.96%−5.02%). The energy proportion of the body region, pantograph region, and other regions increases with the speed, in accordance with the aerodynamic noise.

(3) In the embankment section, the overall sound power level of the train and that of each divided region show different logarithmic growth trends for different train speeds. An evident dividing point appears around 250 km/h, and the rates of noise growth with the train speed before and after the dividing point are different.

(4) For the embankment and viaduct sections, the rule of variation the overall sound power, lower parts, and bogie with speed follows the feature of approximately $20\log(V/V_0)$ when the speed is below 250 km/h, which is dominated by wheel-rail noise. When the speed exceeds 250 km/h the feature turns to approximately $35\log(V/V_0)$, the effect of aerodynamic noise becomes gradually evident and the regression coefficients in the embankment section are larger than those in the viaduct section. The regression coefficients of the pantograph are quite similar, 52.53 in the viaduct section and 51.45 in the embankment section. The characteristic of aerodynamic noise is evident and thus deserves attention.

Data Availability

The data used to support the findings of this study are available from the corresponding author upon request.

Conflicts of Interest

The authors declare that they have no conflicts of interest.
Acknowledgments

The work was supported by the National Natural Science Foundation of China (No.U1934203), and the authors would like to thank the State Key Laboratory of Traction Power for providing office, equipment, and materials to this project.

References

[1] D. J. Thompson, E. Latorre Iglesias, X. Liu, J. Zhu, and Z. Hu, "Recent developments in the prediction and control of aerodynamic noise from high-speed trains," International Journal of Reality Therapy, vol. 3, no. 3, pp. 119–150, 2015.

[2] X.-S. Jin, "Key problems faced in high-speed train operation," Journal of Zhejiang University-Science, vol. 15, no. 12, pp. 936–945, 2014.

[3] Y. Zhao, Z. Yang, Q. Li, and C. Xia, "Analysis of the near-field and far-field sound pressure generated by high-speed trains pantograph system," Applied Acoustics, vol. 169, Article ID 107506, 2020.

[4] K. Nagakura, "Localization of aerodynamic noise sources of Shinkansen trains," Journal of Sound and Vibration, vol. 293, no. 3–5, pp. 547–556, 2006.

[5] N. I. Ivanov, I. S. Boiko, and A. E. Shashurin, "The problem of high-speed railway noise prediction and reduction," Procedia Engineering, vol. 189, pp. 539–546, 2017.

[6] M. Xi, S. Q. Zhong, T. S. Deng, Z. W. Zhu, and X. Z. Sheng, "Analysis of source contribution to pass-by noise for a moving high-speed train based on microphone array measurement," Measurement, vol. 174, Article ID 109058, 2021.

[7] D. H. Johnson and D. E. Dudgeon, Array Signal Processing: Concepts and Techniques, Prentice-Hall, New Jersey, USA, 1993.

[8] J. Billingsley and R. Knims, "The acoustic telescope," Journal of Sound and Vibration, vol. 48, no. 4, pp. 485–510, 1976.

[9] W. F. King III and D. Bechert, "On the sources of wayside noise generated by high-speed trains," Journal of Sound and Vibration, vol. 66, no. 3, pp. 311–332, 1979.

[10] B. Barsikow and W. F. King III, "On removing the Doppler frequency shift from array measurements of railway noise," Journal of Sound and Vibration, vol. 120, no. 1, pp. 190–196, 1998.

[11] P. Chiariotti, M. Martarelli, and P. Castellini, "Acoustic beamforming for noise source localization-rt," Mechanical Systems and Signal Processing, vol. 120, pp. 422–448, 2019.

[12] J. J. Christensen and J. Hald, Technical Review Beamforming, pp. 3–12, Bruel&Kjear, Danmark, 2004.

[13] M. G. Dittrich and M. H. A. Janssens, "Improved measurement methods for railway rolling noise," Journal of Sound and Vibration, vol. 231, no. 3, pp. 595–609, 2000.

[14] B. Schulte-Werning, K. Jäger, R. Strube, and L. Willenbrink, "Recent developments in noise research at Deutsche Bahn (noise assessment, noise source localization and specially monitored track)," Journal of Sound and Vibration, vol. 267, no. 3, pp. 689–699, 2003.

[15] Silence, Report on Source Ranking on State of the Art Validation Platforms and Final Priorities for Research Effort, European Commission, Austria, 2005.

[16] T. Thron, "A Contribution to the Noise Prediction Based on Recognized Metrological Model Parameters," PhD Thesis, Technical University of Berlin, Berlin, Germany, 2010.

[17] C. Mellet, F. Létourneaux, F. Poisson, and C. Talotte, "High speed train noise emission: latest investigation of the aerodynamic/rolling noise contribution," Journal of Sound and Vibration, vol. 293, no. 3, pp. 535–546, 2006.

[18] F. Poisson, P. E. Gautier, and F. Letourneaux, "Noise sources for high speed trains: a review of results in the TGV case," Noise and Vibration Mitigation for Rail Transportation Systems, vol. 99, pp. 71–77, 2008.

[19] H. Koh, W. You, H. Kwon, and D. Lee, "Noise source identification of Korean high speed train," in Proceedings of the 14th International Congress on Sound and Vibration, pp. 1498–1503, Cairns, Australia, January 2007.

[20] D. J. Thompson, Railway Noise and Vibration: Mechanisms, Modelling and Means of Control, pp. 3–9, Elsevier, Amsterdam, Netherlands, 2008.

[21] Y. Wakabayashi, T. Kurita, H. Yamada, and M. Horuchi, "Noise measurement results of shinkansen high-speed test train (FASTECH360S, Z)," Noise and Vibration Mitigation for Rail Transportation Systems, vol. 99, pp. 63–70, 2008.

[22] H.-M. Noh, S. Choi, S. Hong, and S.-W. Kim, "Investigation of noise sources in high-speed trains," Proceedings of the Institution of Mechanical Engineers-Part F: Journal of Rail and Rapid Transit, vol. 228, no. 3, pp. 307–322, 2013.

[23] H.-M. Noh, "Noise-source identification of a high-speed train by noise source level analysis," Proceedings of the Institution of Mechanical Engineers-Part F: Journal of Rail and Rapid Transit, vol. 231, no. 6, pp. 717–728, 2017.

[24] B. He, X.-S. Jin, Q. Zhou, Z. H. Li, and X. S. Jin, "Investigation into external noise of a high-speed train at different speeds," Journal of Zhejiang University-Science, vol. 13, no. 12, pp. 1019–1033, 2014.

[25] X. Zhang, G. Squicciarini, and D. J. Thompson, "Sound radiation of a railway rail in close proximity to the ground," Journal of Sound and Vibration, vol. 362, pp. 111–124, 2016.

[26] J. Han, S.-Q. Zhong, X. Zhou, X.-B. Xiao, G.-T. Zhao, and X.-S. Jin, "Time-domain model for wheel-rail noise analysis at high operation speed," Journal of Zhejiang University-Science, vol. 18, no. 8, pp. 593–602, 2017.

[27] X. Sheng, T. Zhong, and Y. Li, "Vibration and sound radiation of slab high-speed railway tracks subject to a moving harmonic load," Journal of Sound and Vibration, vol. 395, pp. 160–186, 2017.

[28] J. Zhang, X. B. Xiao, D. W. Wang, Y. Yan, and J. Fan, "Source contribution analysis for exterior noise of a high-speed train: experiments and simulations," Shock and Vibration, vol. 2018, Article ID 5319460, 13 pages, 2018.

[29] X. Zhang, R. Liu, Z. Cao, X. Wang, and X. Li, "Acoustic performance of a semi-closed noise barrier installed on a high-speed railway bridge: measurement and analysis considering actual service conditions," Measurement, vol. 138, pp. 386–399, 2019.

[30] P. M. Morse and K. U. Ingard, Theoretical Acoustics, Princeton University Press, New Jersey, USA, 1986.

[31] Z. G. Chu, Y. Yang, and Z. H. Jiang, "Study on the beamforming performance of microphones array," Chinese Journal of Sensors and Actuators, vol. 24, no. 5, pp. 665–670, 2011.

[32] K. Ehrenfried and L. Koop, "Comparison of iterative deconvolution algorithms for the mapping of acoustic sources," AIAA Journal, vol. 45, no. 7, pp. 1584–1595, 2007.

[33] Z. G. Chu and Y. Yang, "Comparison of deconvolution methods for the visualization of acoustic sources based on cross-spectral imaging function beamforming," Mechanical Systems and Signal Processing, vol. 48, no. 1–2, pp. 404–422, 2014.

[34] Z. Chu, C. Chen, Y. Yang, and L. Shen, "Two-dimensional total variation norm constrained deconvolution beamforming
algorithm for acoustic source identification,” *IEEE Access*, vol. 6, pp. 43743–43748, 2018.

[35] ISO (International Organization for Standardization), *Acoustics-railway Applications—Measurement of Noise Emitted by Railbound Vehicles*, ISO, Geneva, Switzerland, 2013.

[36] P. Sijtsma and H. Holthuisen, “Corrections for mirror sources in phased array processing techniques,” in *Proceedings of the The 9th AIAA/CEAS Aeroacoustics Conference and Exhibit*, South Carolina, USA, May 2003.

[37] F. Fahy, “Sound absorption and sound absorbers,” *Foundations of Engineering Acoustics*, Elsevier Academic Press, Cambridge, USA, pp. 140–180, 2001.

[38] J. F. Allard and N. Atalla, *Propagation of Sound in Porous Media: Modelling Sound Absorbing Materials*, pp. 20–23, A John Wiley and Sons Ltd, Publication, Chichester, UK, 2009.

[39] M. Meskine, F. Pérot, M.-S. Kim et al., “Community noise prediction of digital high speed train using LBM,” in *Proceedings of the Aiaa/ceas Aeroacoustics Conference*, Berlin, Germany, January 2013.

[40] R. Cui, L. Gao, X. Cai, and B. Hou, “Vibration and noise reduction properties of different damped rails in high-speed railway,” *Noise Control Engineering Journal*, vol. 62, no. 4, pp. 176–185, 2014.

[41] M. Podile, D. V. V. Kallon, B. M. Balekwa, and M. Cali, “Design and modeling of viscoelastic layers for locomotive wheel damping,” *Vibrations*, vol. 4, no. 4, pp. 906–937, 2021.