A method has been developed for predicting the aerodynamic noise from the bogie of a high-speed train using a two-dimensional microphone array in a low-noise wind tunnel. First, the flow velocity in the rail direction was measured in a field test at several points along the sleeper direction under the train car. Second, the flow distribution was reproduced precisely in a low-noise wind tunnel. Third, aerodynamic noise generated by the bogie (“aerodynamic bogie noise”) was estimated from the noise source distribution measured with a two-dimensional microphone array. Finally, based on the experimental results, the noise generated from the lower part of the car (i.e. the aerodynamic noise estimated through the proposed method and the rolling and machinery noise estimated in a previous study) was compared with field test data measured near the track. The estimated lower part noise levels showed good agreement with those measured in the field test. This suggests that the proposed method is valid for the quantitative estimation of aerodynamic bogie noise. It was also shown that the contribution of the aerodynamic bogie noise is greater than the rolling and machinery noise, especially in the low-frequency region.

Keywords: aerodynamic bogie noise, wind tunnel test, microphone array

1. Introduction

Noise generated by high-speed trains is a major environmental problem, and many attempts have been made to reduce it [1]. Main noise sources around a Shinkansen can be categorized as (1) pantograph aerodynamic noise, (2) aerodynamic noise generated from the upper part of the cars, (3) bridge noise and (4) noise generated from the lower parts of the cars (hereafter, lower part noise). Normally, the noise level of a Shinkansen train is assessed at a reference point of 25 m away from the center of the nearest track. Even in places where acoustic barriers are installed, lower part noise makes greater contribution to accounts the total noise measured at the reference point, and aerodynamic noise has been shown to be dominant source of that lower part noise, especially at speeds above 300 km/h [2]. However, in [2], the contribution of aerodynamic noise has not been explicitly estimated. A quantitative evaluation of aerodynamic noise requires accurate measurement of the flow field under the train car, to form a better understanding of the complicated mechanisms underlying aerodynamic noise generated by bogies (hereafter, aerodynamic bogie noise). Past studies have attempted to estimate aerodynamic bogie noise in wind tunnel tests, where only the vertical flow velocity profile along the centerline of the train body was simulated [3]. However aerodynamic bogie noise was also considered to be strongly affected not only by the flow field at the center of the train body but also the whole flow field under the car. Therefore, this paper proposes a method to estimate aerodynamic bogie noise while considering the whole flow field obtained experimentally. As the first step in this study, the flow velocity component in the rail direction was measured in a field test, at several points along the sleeper direction under the train car (hereafter, flow distribution along the sleeper direction). Next, the flow distribution along the sleeper direction was simulated precisely in a wind tunnel test. Aerodynamic bogie noise was then estimated from the noise source distribution obtained by a two-dimensional microphone array. Finally, the proposed method was validated by comparing the estimated lower part noise, comprising the aerodynamic noise estimated by the proposed method and the rolling and machinery noise according to the method in ref. [2], with results obtained from field measurements.

2. Field test: velocity measurement under the train car

2.1 Measurement methods

This section describes the methods used to measure flow velocity distributions under the vehicle floor during the passage of a train. Nine one-dimensional hot-wire anemometers were installed in the sleeper direction along a slab-track Shinkansen line (Fig. 1). The flow velocity was measured in the rail direction as Shinkansen trains passed over them. The coordinate origin was set at the surface of
the rail head (hereinafter referred to as R.L.) at the center of the track. The traveling direction of the vehicle was used as the positive direction of the X axis, and the direction to the right of an observer facing the train tail was the positive direction of the Y-axis, and the vertical direction was the positive direction of the Z-axis. Seven sensors (R1-R7) were installed at a height of -15 mm (Z = -15mm). Constant-temperature-type thermal anemometers were used for the hot-wire anemometers, which are able to detect the magnitude of the vertical velocity component perpendicular to a hot-wire sensor. In this measurement, the velocity component in the sleeper direction was not measured. Moreover, in order to measure train speed, an axle detector was used. The output from the hot-wire anemometers and axle detector were passed through amplifiers, recorded on a PC via an analog-to-digital (A/D) converter (± 6.0V, 24 bit). The sampling frequency of the A/D conversion was 2 kHz, and the anti-aliasing filter had a cut-off frequency of 1 kHz.

2.2 Data analysis

A typical result of the under-floor flow velocity induced by the passage of a Shinkansen train (time-series data from R1) is given in Fig. 2. The under-floor flow velocity, measured on the ground, is found to be influenced by the passage of the individual vehicle parts. Therefore, the average flow velocity during the passage of each section of the vehicle in one train set was evaluated as shown in Fig. 3 (hereinafter referred to as the evaluation section). The ensemble average velocity of the time-average flow velocities of all trains (eleven trains) that were measured was also calculated. Hereinafter, the value of the ensemble average velocity is described simply as flow velocity. The distribution of these flow velocities in the rail direction and the sleeper direction is discussed in the following sections.

2.3 Measurement results

2.3.1 Flow velocity during the passage of a train

In this measurement, the under-floor flow velocities were measured on the ground side. The measured flow velocity was treated as normalized by the train speed, and the results were expressed on the ground-fixed coordinate system. It can be seen from Fig. 2 that, in the section from the nose to car No. 2, the flow velocity increases sharply,
and then becomes almost constant. This is in good agreement with the result of previous study [4]. The maximum flow velocity was observed during the passage of the tail of the train.

2.3.2 Flow velocity distribution in the rail direction

Figure 4 shows the average flow velocity distribution in the evaluation section of each hot-wire anemometer. The horizontal axis shows the distance from the origin to the evaluation section. The origin is the edge of the leading vehicle. The vertical axis shows the averaged value of the non-dimensional flow velocity of the under-floor flow. It can be seen that the flow velocity at the center of the track (at R1) was higher than those at other measurement points across the track for car No.2 and the following cars. In each section, we find that the flow velocity from car No.2 to the trailing vehicle is gradually increased.

![Flow velocity distribution in the rail direction on a ground-fixed coordinate system](image)

**Fig. 4** Flow velocity distributions in the rail direction on a ground-fixed coordinate system

2.3.3 Flow velocity distribution in the sleeper direction

Figure 5 shows the non-dimensional flow velocity distribution in the sleeper direction, in the leading vehicle and the intermediate vehicle (car No.5). The horizontal axis shows the sleeper direction position of the sensors R1-R7. The vertical axis shows the average value of the non-dimensional flow velocity of the under-floor flow. Results from car No.5 were used to represent an intermediate vehicle, because the flow velocity distribution of the intermediate vehicle was almost constant, as against the variation of the flow velocity of the leading vehicle and the tail section as shown in Fig. 4. A significant difference was found between the flow velocity distribution at the leading vehicle and the intermediate vehicle. In the intermediate vehicle, it was found that the average flow velocity in the sleeper direction was 30%-40 % of the train speed. The flow velocities at the nose section of sensors R1-R7 were lower than those at the other sections. After the passage of the front bogie, the flow velocity increased, because the air near the vehicle body that has large velocity was moved by the passage of the bogie. The effect of the air near the vehicle reached the far region from the vehicle. In particular, the flow velocities near the rail were high, which suggests that the under-floor flow was strongly influenced by the wheels. In the intermediate vehicle, including the front bogie, the rear bogie, and the inter-vehicle gap, a tendency for the flow velocity to decrease serially from R1 to R7 was detected, with the exception of R6, which was underneath the side edge (Fig. 1).

![Flow velocity distributions in the sleeper direction at every measurement point for car No.5 on a ground-fixed coordinate system](image)

**Fig. 5** Flow velocity distributions in the sleeper direction at every measurement point for car No.5 on a ground-fixed coordinate system

3. Wind tunnel tests

3.1 Flow velocity profile adjustment

Based on the results reported in Section 2, the flow velocity distribution at the front and rear bogies was simulated, to investigate the aerodynamic bogie noise of the leading vehicle and the intermediate vehicle in the wind tunnel test. In particular, the flow velocity distribution was simulated with a focus on the following two points. First, the flow velocity in the sleeper direction at the intermediate vehicle is approximately 40% of the train speed at the center of the track (y = 0 mm) and decreased gradually to 30% toward the side of the body. Second, at the leading vehicle, the flow velocity was lower than that at the intermediate vehicle when measured in the ranges y = 0~600 mm and 1200~1700 mm.

Figure 6 shows the setup of the wind tunnel test. The x, y, and z directions were defined as the main flow, horizontal, and vertical directions, respectively. A 1/7-scale train model was installed on the ground plate with two supporting struts at the front and rear model cars. Figure 7 shows the test conditions for the bogie section. The bogie model was installed inside the cavity, as shown in Fig. 7(a). During the measurement of the aerodynamic bogie noise, both sides of the bogie were fully covered (Fig. 7(b)). Background noise was defined as the data measured under a flat condition with no cavity (Fig. 7(c)). As shown in Fig. 6(b), an acoustic barrier was set at the side of the train model to screen the noise propagating from the struts located at the train head. The velocity at the inlet of the bogie section was measured through a pitot tube rake.

Since the flow velocity measured under the intermediate vehicle of the train was about 60 % of the train speed on the train fixed coordinate, as shown in Fig. 5, two methods were used to adjust the velocity profile (noting that the velocity was plotted on the ground-fixed coordinate system in Fig. 5), as follows:

1. Using a free shear layer around the nozzle exit.

This was intended to decrease the flow velocity around...
Fig. 6  Schematic of the experimental setup of a wind tunnel test

(a) Top view

(b) Side view

Fig. 7  Conditions of the bogie section

(a) Bogie model

(b) Bogie model with side covers

(c) Flat model without bogie

Fig. 8  Methods used to adjust the flow distribution under the train car model.

(a) Method 1 (Free shear layer around the nozzle exit)

(b) Method 2 (Flow adjustment parts)
the bogie section. Figure 8(a) shows the schematic layout of the free shear layer around the nozzle exit with a velocity gradient. The velocity at the inlet of the bogie section was adjusted by changing the position of the model in the free shear layer to the nozzle exit, i.e., by changing the distance, $H$, between the lower edge of the nozzle exit and the ground level. Figure 9 shows the effect of the distance, $H$, on the flow velocity distribution in the sleeper direction. The velocity decreased over the entire width in the sleeper direction as $H$ increased.

(2) By installing flow adjustment parts under the car.

As shown in Fig. 8(b), a pair of elliptically shaped parts was installed on the rail located upstream of the bogie section. By changing the widths, $L_1$ and $L_2$ of these parts (Fig. 8(b)), the velocity defect region was used to obtain an appropriate velocity distribution. Figure 10 shows the effect of the parts on the velocity distribution. The mean flow velocity inside the rail ($v < 800$ mm) was adjusted properly by changing the width of the parts. $H$, $L_1$, and $L_2$ were determined as follows, to simulate a flow distribution of field test for the leading and intermediate vehicles:

- Leading vehicle: $H = 0$ mm, $L_1 = L_2 = 20$ mm
- Intermediate vehicle: $H = 175$ mm with no parts

Figure 11 shows the flow distributions in the sleeper direction under the leading and intermediate vehicles obtained from the field test and wind tunnel test: the two distributions were in good agreement.

### 3.2 Methods for estimating aerodynamic bogie noise

This section describes the procedures used to estimate the aerodynamic bogie noise in the wind tunnel test. First, the two-dimensional sound distribution of aerodynamic bogie noise was measured using a two-dimensional microphone array. The distribution of aerodynamic bogie noise source was then obtained by applying a conventional delay-and-sum beam-forming algorithm under the flow conditions described in section 3.1. The two-dimensional microphone array system had a radius of approximately 1 m and consisted of 66 microphones. Sound pressure level (SPL) distribution of up to 2 kHz band in a full-scale model could be obtained by using it. The microphone array was installed 3.5 m away ($r = 3.5$ m) from the train center.

The SPL, $L_W^W(f)$, was calculated from an omni-directional microphone using the following equations:

$$L_W^W(f) = 10 \log_{10} 10^{\left( \frac{L_{\text{int}}(f) - C(f) + A(f)}{10} \right)} - 10^{\left( \frac{L_{\text{BGN}}(f) - C(f) + A(f)}{10} \right)}$$

(1)

$$C(f) = L_{\text{int}}^A(f) - L_{\text{int}}^{\text{BGN}}(f)$$

(2)

where the conversion coefficient $C$ is derived from $L_{\text{int}}^A(f)$ which is the SPL measured by the omni-directional microphone. $L_{\text{int}}^A(f)$, $L_{\text{int}}^{\text{BGN}}(f)$ and $L_{\text{int}}^{\text{BGN}}(f)$ are the SPL averaged over an area around the bogie section in the two-dimensional SPL distribution measured by the microphone array. Superscript $A$, $A$ and $BGN$ indicate the measured value of the bogie condition without side covers (Fig. 7(a)), bogie condition with side covers (Fig. 7(b)) and flat bogie condition (Fig. 7(c)) respectively. In this study, $L_{\text{int}}^A(f)$ and $L_{\text{int}}^{\text{BGN}}(f)$ were measured when only the bogie was set as shown in Fig. 7(a). The signal-to-noise ratio

![Fig. 9 Flow velocity distribution at the positions inside the free shear layer on a train-fixed coordinate system](image1)

![Fig. 10 Flow velocity distribution by flow adjustment parts on a train-fixed coordinate system](image2)

![Fig. 11 Flow velocity distribution in the sleeper direction on a train-fixed coordinate system](image3)
(SNR) in this condition was sufficient to estimate the coefficient $C$. 

Finally, the noise level measured at 2m from the centre of the track and 0.4 m above the railhead (hereafter, railway nearby noise) was estimated. Figure 12 shows the geometries of the reference microphone and bogie section. All units in this figure are described in full scale. The distance between the analysis planes, including the car center line and the microphone array in the wind tunnel test, corresponded to 24.5 m (plane A) at full scale. The noise source $S$ was assumed to be located on the car floor. On the basis of the geometries of the noise source, $S$, and the noise measurement point, $N$, the microphone at point $M$ was chosen from the array as the reference microphone.

Figure 13 shows the frequency characteristics of the conversion coefficient, $C$. As the spatial resolution of the microphone array became poorer at lower frequency regions, $C$ increased. Figure 14 shows the SNR of the aerodynamic bogie noise measured by the microphone array and omnidirectional microphone under the bogie conditions, as shown in Fig. 7(b). An SNR greater than 5 dB was observed below the 1 kHz band when measured with the microphone array, whereas the SNR was less than 3 dB when measured with the omnidirectional microphone. This suggests that the use of a microphone array is necessary for the quantitative analysis of aerodynamic bogie noise. Figure 15 shows the time history of the railway nearby noise. The SPLs corresponding to the leading and intermediate car bogies were obtained by averaging the SPLs during the passage of two neighboring bogies. The noise level at point $N$ was calculated by (3):
\[ L^F = L^W + 20\log_{10}(\alpha r) + 10\log_{10}(\eta) \]

where \( \alpha \) (= 1/7) is the model scale and \( \eta \) (= 2) is the number of bogies, \( r \) (= 3.5 m) is the distance from the model center to the microphone array in the wind tunnel test as shown in Fig.6 and \( r_L = 2717.5 \text{ mm} \) is the distance between the train center to the noise measurement point \( N \) in Fig.12.

### 3.3 Validation of the estimated aerodynamic bogie noise

In order to validate the proposed methods, estimated aerodynamic bogie noise was compared with the lower part noise in the field test. Because the lower part noise consists of the rolling and machinery noise besides the aerodynamic bogie noise, estimated rolling and machinery noise obtained by [2] was added to the noise level calculated by (3). Figure 16 shows a comparison of the lower part noise of the intermediate vehicle estimated in the wind tunnel test with that obtained from the field tests. When estimating the lower part noise, the rolling and machinery noises were combined, in [2]. The estimation error was defined as the averaged SPL difference between the field test and the estimation at each 1/3 octave frequency band. The total estimated lower part noise levels were in good agreement with those from the field test within an estimation error of about -2 dB. This suggests that the proposed method is valid for the quantitative estimation of aerodynamic bogie noise. The results also show that the aerodynamic bogie noise estimated from the wind tunnel tests, which had a peak at approximately 400 Hz, was close to those from the field test, in a frequency range from 125 to 500 Hz. This suggests that, in this frequency range, aerodynamic noise plays a greater role in the lower part noise than the rolling and machinery noise.

Figure 17 shows the lower part noise for the leading and intermediate vehicles. The difference in noise between the cars was about 4 dB in both the field studies and wind tunnel tests. Table 1 shows the mean flow velocities, \( V_L \) and \( V_M \), for the leading and intermediate vehicle, respectively. In Case 1, the velocity was obtained by averaging the flow velocity over the all sleeper positions, whereas in Case 2, the velocity was obtained at the centerline (\( y = 0 \) mm). It was assumed that the power of the aerodynamic noise increases in proportion to the \( 6 \)th power of the flow velocity, and the difference in SPL between the two cars was estimated as follows:

\[ \Delta L = 60\log_{10}(V_L/V_M) \]  (4)

In Case 1, the difference in the noise level was estimated at approximately \( 60\log_{10}(0.76/0.64) = 5 \text{dB} \), which agrees well with the results shown in Fig. 17. However, the noise level difference in Case 2 was \( 60\log_{10}(0.79/0.59) = 8 \text{dB} \), which is much greater than the results in Fig. 17. This difference suggests that flow distribution along the sleeper direction has a significant influence on the aerodynamic bogie noise and should be simulated correctly to evaluate the aerodynamic bogie noise through wind tunnel tests.

### 4. Conclusions

We developed a method for quantitative estimation of aerodynamic bogie noise using wind tunnel tests. The flow distribution in the sleeper direction under a train car was obtained through field test. The velocity distributions of the leading and intermediate vehicle were precisely simulated in a wind tunnel test. Aerodynamic bogie noise was then estimated from the noise source distribution obtained by a two-dimensional microphone array. The estimated lower part noise including the aerodynamic bogie noise obtained through the proposed method agrees well to that obtained in the field test. It was shown that the contribution of the aerodynamic bogie noise is greater than that of both the rolling and machinery noise, especially below 500
Hz. From the comparison of the aerodynamic bogie noise of the middle and the leading vehicles, it was also shown that flow distribution along the sleeper direction should be correct to evaluate the aerodynamic bogie noise through wind tunnel tests.

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