Wind Tunnel Tests on Reduction of Aeroacoustic Noise from Car Gaps and Bogie Sections

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In this study, we propose techniques for reducing aeroacoustic noise from gaps between cars and bogie sections. A microphone array placed adjacent to the main flow of the wind tunnel is used as a measurement device to improve the spatial resolution and the accuracy of identifying the noise sources. The results show that aeroacoustic sound sources at gaps between the cars are sufficiently weakened by rounding corners of cars, because the impact of impinging vortices at the corners is relieved and efficiency of acoustical radiation is reduced. Noise from the bogie sections is also reduced by installing side covers, slopes and round corners.

Keywords: noise reduction, gaps between adjacent cars, bogie, microphone array

1. Introduction

The Japanese government's Environmental Quality Standards for Shinkansen Super express Railway Noise prescribes that the maximum A-weighted sound pressure level (slow) of a train set passing $L_{pA, Smax}$ at the wayside of the track shall be 70dB(A) or less in areas that are mainly residential and 75dB(A) or less in other areas including commercial and industrial areas, where normal living conditions should be preserved¹⁾. Although spark noise from the pantograph and rolling noise were typical noise sources when Shinkansen trains commenced operation in October 1964, most of these sounds have now been effectively reduced through a number of noise reduction techniques. However, new issue of aerodynamic noise has attracted a considerable amount of attention lately. The type of noise is generally caused by flow disturbance around uneven areas on the train body, and its power increases in proportion to the 6th powers of train speeds. For example, pantograph noise is a typical aerodynamic noise issue because of the difficulty in shielding it with a noise barrier on the ground. A number of aerodynamic approaches have proposed optimized shapes for noise reduction such as the streamlined pantograph-head²⁾. Against this background, the contributions of noise from gaps between adjacent cars and the bogie section to environmental noise has seen a relative increase.

The Railway Technical Research Institute (RTRI) used the Large-scale Low-noise wind tunnel in Maibara city (MWT) to study the generation mechanisms of aeroacoustic noise and techniques for its reduction. As a basis for the process toward achieving proper noise reduction techniques, accurate noise source localization is essential to determine which parts are responsible for noise generation, especially in the case of using a small-scale model in wind tunnel testing. In this study, we first attempted to improve the accuracy of noise source localization by installing a microphone array near the model, and closely examined the influence of the free shear layer around the main flow on the acoustic characteristic. Secondly, noise reduction techniques for the gap between

adjacent cars and bogie sections were presented on the basis of the noise source localization results.

2. Development of a microphone array adjacent to the main flow

2.1 Sound path model in an open test section

In taking measures to reduce aerodynamic noise, accurate noise source localization at the initial stage is of great importance. Particularly high spatial resolution and accurate position estimation are essential in investigating noise distribution around a narrow gap section. In the MWT, noise source distribution has so far been obtained by using directional microphone systems such as an acoustic mirror and an X-shaped microphone array specially designed for wind tunnel testing^{3) 4)}. In particular, the microphone array is useful because it enables the desired focal point to be set and the measurement time to be shortened. In the signal processing of the microphone array, the acoustic phase is corrected on the basis of the distance from the focal point to each microphone⁵⁾. It is therefore necessary to estimate the exact propagation distance for accurate source localization.

The conventional directional microphone systems mentioned above are installed in the area outside the free shear layer which includes strong turbulence. Provided that the free shear layer is infinitely thin and parallel to the main flow direction, the sound path at the open test section of a wind tunnel is modelled as shown in Fig.1. The sound wave originating at source point A is convected downstream, refracted at position C in the free shear layer around the main flow, then reaches microphone position D. The influences of the convection and refraction are expressed by Equations (1) and (2) based on the geometrical relations shown in Fig. 1⁶⁾.

$$(\cos\alpha + M)/\sin\alpha = 1/\tan\beta \quad (1)$$

$$1/\cos\alpha + M = 1/\cos\gamma \quad (2)$$

Fig. 1 Geometry of the sound path model in the open test section of the wind tunnel

where M is the Mach number of the main flow. However, it is difficult to accurately predict the sound propagation path in practice because the free shear layer changes its width and flow velocity with respect to time and space. This problem results in a deterioration of the source localization accuracy. Furthermore, the signal to noise ratio decreases due to the acoustic scattering in the free shear layer. We therefore designed a microphone array to be installed adjacent to the main flow (referred to as a near-flow microphone array) so as to avoid being affected by the free shear layer. Angle γ in Fig.1 is then omitted, and the length of the sound path is simply estimated using only Eq.(1).

2.2 Performance tests using a standard source device

We conducted performance testing to investigate the relationship between the directivity of the microphone array and its setting position in the free shear layer. Figure 2 shows the experimental test set-up using a standard source device, which was installed at $X = 1,750$ mm and $Y = 0$ mm. The microphone array was installed at $X = 2,000$ mm and distant from the centerline by Y_a . The value of Y_a varies from 1,500 mm denoting the extended line of the nozzle sidewall to 2,400 mm at intervals of 300 mm. 64 microphones were arranged in a spiral pattern and mounted flush on a square board surface with a side of 1,300 mm as shown in Fig. 2 (b). Flow-induced noise was suppressed by the cross spectrum method obtained by the outputs of two pairs of microphone arrays⁷⁾. The board was also coated with urethane foam to a thickness of 10 mm. The analysis region is a square of 600 mm x 600 mm, and its lattice size is adjusted from 1 mm to 10 mm depending on the desired accuracy. The velocity profiles around the free shear layer were measured using a hotwire anemometer at a uniform wind velocity of $U = 200$ km/h and a position of $X = 2,000$ mm.

The non-dimensional mean velocity and the turbulence level components in the X -direction are plotted against the Y -direction in Fig.3. The mean velocity shows a sharp change between $Y = 1,400$ mm and $Y = 1,700$ mm, and the turbulence level also increases in the same region. Figure 4 shows the sound pressure level distributions around the source device at a wind velocity of $U = 300$ km/h. This result indicates that the source position can be clearly obtained in the case closest to the main flow, i.e. $Y_a = 1,500$ mm. Figure 5 shows the difference in

Fig. 2 Experimental setup for performance tests of the microphone array with a standard source device

Fig. 3 Velocity profiles around the free shear layer against the Y direction at $U = 200$ km/h

Fig. 4 Comparison of sound pressure level distributions around the standard source device at $f = 10$ kHz one-third octave band, $U = 300$ km/h

maximum sound pressure level in Fig. 4 compared to that with no wind. In the case of $Y_a = 1,500$ mm, sound waves from the standard source device can be detected accurately. Figure 6 shows a comparison of source location errors measured using the near-flow microphone array installed at $Y_a = 1500$ mm in the free shear layer and X-shaped microphone array⁴⁾ installed outside at $Y_a = 5000$ mm. The accuracy of source localization using the near-flow microphone array is improved to a location error of better than 10 mm, which is suitable for narrow areas such as the gap sections of a scaled train model. We can therefore conclude that clear and accurate noise source localization is made possible by installing the microphone array at the closest position to the main flow, i.e. $Y_a = 1500$ mm.

3. Wind tunnel testing using a 1/8 scale train model

3.1 Experimental method

We investigated the noise characteristics of the gap

and bogie sections using a 1/8-scale train model. Figure 7 shows the experimental set-up of the train model and microphones. Based on the results outlined in Section 2.1, we installed the microphone array at $Y_a = 1,500$ mm. The A-weighted sound pressure level (the noise level) was also measured using an omni-directional microphone. As shown in Fig. 7 (b), it was set 3,125 mm away from the nozzle center to correspond to the typical noise assessment point of Shinkansen trains (i.e. the 25m point) on a real scale. Frequency f appearing in this chapter is expressed as a frequency corrected to the real scale. Figures 8 and 9 show the test conditions of the gap and bogie sections. The train model consisted of the first car and a shortened second car with lengths of 3,275 mm and 1,087.5 mm respectively. These cars were set at an interval of 62.5 mm corresponding to 1/8 of the real gap interval, and the bogies including the wheels were modelled precisely. The model had supports of 50 mm in height, and was installed on a rail 50 mm above the floor. This interval of 100 mm between the floor and the base of the train model corresponds to twice the distance between the top of the rail and the ground on a real scale. The following sections outline the details of the measures against noise reduction. Noise source distributions around

the gap and bogie sections were analysed on a plane that included the train body side and the wheels respectively. In the analysis of the bogie section, the sound path should be considered not only for direct waves but also for reflected waves as shown in Fig. 10. That is, the contribution of the reflected sound wave was obtained by analysing the mirror image.

The difference between the shear layer thickness of the model and a real train, which affects aeroacoustic noise generation, should be examined in advance. The thinner shear layer around the 1/8-scale model can cause strong tonal noise from the gap. From previous studies in which pressure fluctuations inside a gap section were examined, it is known that treatment involving roughness or wire on the upstream edge is effective in controlling the shear layer thickness. We therefore placed a wire with a diameter of 2 mm along the body edge 50 mm upstream from the edge of the first car.

3.2 Noise reduction techniques for gaps between adjacent cars

In this section, we consider the case of gaps between adjacent cars. In the current condition, the outer hood covers the gap up to its shoulder as illustrated in Fig. 8 (a). Shown in Fig. 11 (a) is the noise source distribution

Fig. 5 Difference in sound pressure level against Y_a

Fig. 6 Comparison of location errors in position estimation

(a) Setup for noise source localization tests with microphone array

(b) Setup for noise level measurements with omni-directional microphone

Fig. 7 Experimental setup for noise measurements in the open test section of Large-Scale Low-Noise Wind Tunnel

Fig. 8 Shapes of gap section of 1/8 scaled train model

Fig. 9 Bogie section of 1/8 scaled train model

Fig. 10 Geometry of the sound path model with a noise source near the floor

around the gap with the outer hood in an $f = 315\text{Hz}$ one-third octave band. It is clear that a noise source exists below the hood, and the phenomenon is observed more clearly without the outer hood. Figure 11 (b) shows a strong noise source along the downstream edge. This result suggests that the impinging vortex motion on the downstream edge is related to strong aeroacoustic noise generation. Sharp edges should also be considered as

strengthening acoustic wave generation because of their acoustic radiation efficiency.

Although several measures to counter these noise problems have been adopted so far, most of them have been focused on conventional solutions such as smoothed shapes, exemplified by a cover-all hood to completely enclose the gap⁸⁾. In reality, however, such techniques seem to present difficulties in terms of maintenance and durability. We therefore examined noise reduction techniques involving alteration of the shape of the train itself, and on the basis of several attempts, a rounded-edge shape was found to be effective. Figure 8 (c) shows a gap featuring the rounded edge. The radius of the curvature at the edge is 25 mm on the model scale and 200 mm on the real scale. As shown in Fig. 11 (c), the noise source along the downstream edge is considerably less than that found in the case of a right-angled edge. These results suggest the following three noise reduction factors: firstly, the turbulence level of the shear layer around the gap is reduced; secondly, the impact of the impinging vortex on the downstream edge is weakened; thirdly, the acoustic radiation efficiency is reduced. Figures 12 (a) and (b) indicate the noise level measured using the omni-directional microphone and the results with background noise correction. It is clear that the noise level with the rounded edge decreases in the entire frequency region except for the 80Hz band, and is almost the same with the case of the smoothed condition. According to the results shown in Fig. 12 (b), the noise level with the rounded edge shape is estimated to be approximately 7dB lower than that of the

current condition.

3.3 Noise reduction techniques for the bogie section

The current typical noise source distributions around the bogie section are shown in Figs. 13 and 14 at an $f = 1$ kHz one-third octave band in the direct and reflected sound regions, respectively. It is apparent from the results of the direct sound region that the noise sources around the wheels are predominant in a high-frequency region. We therefore propose two countermeasures as noise reduction techniques. The first step is to install side covers to shield the noise as shown in Fig. 9 (b). The results are outlined in Fig. 13 (b), and suggest that noise sources around the wheels disappear in the direct sound region. However, it should be noted that the noise sources still exist in the reflected sound region as shown in Fig. 14 (b). These results indicate that, although the side covers shield the noise, they do not weaken its source around the bogie section so much in the high-frequency region. We therefore need to reduce the impact of the impinging vortex on the wheel for further noise reduction.

As discussed earlier, rounded edges are effective in reducing noise even in low-frequency regions. We therefore propose combined countermeasures as the second step in the shape of a rounded/sloped floor edge, including the side covers (see Fig. 9 (c)). Here, it should be noted that the side covers were fitted when the measurements were made, and they have been removed in Fig. 9(c) to show

the rounded/sloped shape edge. The height of the slope is 8.75 mm in the model size and 70 mm on the full size scale, while the radius of curvature is 25 mm in the model size and 200 mm in reality. Figures 13 (c) and 14(c) shows the noise reduction effects obtained using these techniques. These countermeasures can control the flow at both the upstream and downstream edges, in that the flow is turned aside at the upstream slope and its impact at the downstream edge is reduced by the rounded-edge shape. According to previous studies, the low frequency component of noise originating from the bogie section relates to its cavity shape^{9) 10)}. From this perspective, the side cover is considered to have another function involving the reduction of noise in the low frequency region by smoothing the side shape of the bogie sections. Figure 15 shows the noise level measured using an omni-directional microphone. The noise reduction effect of the side cover is evident at frequencies above the 100Hz band, and the reduction amount is estimated as approximately 3.2dB. Compared to the case with no countermeasures, the noise level can be reduced by 1.6 dB more using the rounded/sloped edge techniques, and the total reduction is estimated as approximately 4.8 dB.

4. Conclusion

We examined effective noise reduction techniques for the gaps between adjacent cars and the bogie sections of

Fig. 11 Sound pressure level distributions around the gap ($f = 315\text{Hz}$ one-third octave band)

(a) Results without background noise correction (b) Results with background noise correction

Fig. 12 A-weighted sound pressure level of the gap section obtained using an omni-directional microphone

Fig. 13 Noise source distributions around the bogie sections in the direct sound region ($f = 1\text{kHz}$ one-third octave band)

Fig. 14 Noise source distributions around the bogie sections in the reflected sound region ($f = 1\text{kHz}$ one-third octave band)

Fig. 15 Comparison of A-weighted sound pressure level between current bogie condition and counter-measure conditions at $U = 300\text{km/h}$

high-speed Shinkansen trains through wind-tunnel testing. Accurate noise source distributions around the scaled train model were obtained using a microphone array installed inside the free shear layer. Based on the results of these tests, we propose a number of noise reduction techniques. For the gaps between adjacent cars, rounded

edges are effective in noise reduction because they cause a reduction in the strength of the vortex shedding at the upstream edge, its impact on the downstream edge and acoustic radiation efficiency. The amount of noise reduction level obtained using this technique was estimated as approximately 6 to 7dB. For the bogie section, combined countermeasure: rounded - sloped edge shape at the floor and side covers beside the bogie section are effective. The total noise reduction level obtained using these techniques was estimated as approximately 5dB.

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