Study on the Aeroacoustic Noise from Shinkansen with Mirror Image Models

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The effect of aeroacoustic noise on the sound level of Shinkansen train on the ground becomes increasingly important as the maximum speed increases. In order to simulate the effect of the ground that moves relative to the vehicle, a pair of mirror image models are tested at the Maibara Wind Tunnel which has an excellent low background noise level. Sound levels generated by several combinations of front shapes, bogie conditions and inter-car gaps are measured by a sound concentrating microphone with a paraboloidal reflector. Measurements of flow properties show that the noise is mainly generated by the vortices that are separated at the leading edge of the bogie section, travel leeward at the convective flow speed, and then impinge upon the trailing edge of the section.

Keywords: aeroacoustic noise, mirror image models, unsteady flow, cavity tone

1. Introduction

As the maximum speed of Shinkansen train increases, the effect of aeroacoustic noise on the sound level on the ground becomes increasingly important. Aeroacoustic noise from the upper parts of trains was large in the past, but the noise has been reduced by smoothing irregularities. Recently, however, the aeroacoustic noise from the lower parts poses a problem instead. Since the dominant frequency of the aeroacoustic noise is far lower than that of other noise such as rolling noise, it cannot be totally reduced by noise barriers. Therefore, reduction of aeroacoustic noise is one of the key technologies to increase the train speed. There are two problems when the aeroacoustic noise from lower parts of the train is evaluated from the results obtained by a wind tunnel test: (1) The ground moves relative to the vehicle in the real condition. In order to reproduce the flow under the train at a wind tunnel, the relative motion of the ground must be simulated. (2) Scale models must be used because of the limitation of the wind tunnel size. Data acquired must be converted into that of actual scale by some means.

This paper reports experimental results with mirror image models to settle the above problem (1). Computational Fluid Dynamics is also adopted to simulate the mechanism of the unsteady flow at the bogie section and evaluate the validity of the mirror image method.

2. Experimental results

The moving belt ground plane is one of the most suitable ways to simulate the flow under a train in a wind tunnel. Experiments are conducted with 1/25 scale mirror image models, as shown in Fig. 1. Measurement points are labeled from 1 to 8.
tunnel. In acoustic measurement, however, it cannot be used because it is obstructed by the noise itself. Another way to simulate the effect of the ground is a mirror image method, in other words, a pair of mirror image 1/25 scale models are placed symmetrically, and their plane of symmetry is assumed to be the moving ground\(^1\). Fig. 1 shows a schematic diagram of the measurements with 1/25 scale models. Each model consists of five cars and lies on the side. They are fixed on a 8 m-long support table through support legs.

In order to simulate the 400 mm space between the ground and the bottom of the vehicle in the real scale, the space between the symmetrical plane and the bottom of the vehicle is set at 400/25=16 mm. So the space between the mirror image models is set to 32 mm.

Wind tunnel tests are carried out at the Maibara Wind Tunnel. Most measurements are obtained at the wind speed of 300 km/h, with some at 200 km/h and 100 km/h to evaluate the velocity dependency of the sound level. The center of the nozzle exit is set as the origin of the measurement coordinates, main flow direction as the x-axis, and vertical direction as the z-axis. In the case of measurements with hot wire anemometers, the origin of y-axis is changed as described later.

### 2.1 Measurements of unsteady flow with a hot wire anemometer

The velocity profiles of the flow under and over the train are measured first with a hot wire anemometer. The probe used is an I-shaped single sensor manufactured by Dantec, whose hardware frequency limit is 400 kHz. The anemometer is installed at the tip of the traverse device as shown in Fig. 2. The influence of the traverse device itself upon the velocity profile is measured before the mirror image models are set, in order to prove that it has little influence in this measurement.

The velocity profile of the flow under the train is measured at eight cross sections along the models as shown in Fig. 1. In each cross section, the z-position of the anemometer is fixed at the center of the models, and the y-direction is set at 4, 10 and 16 mm from the bottom of the model. The upper chart of Fig. 3 shows the profile of mean velocity, and the lower one shows the profile of turbulence level. The laminar flow at \(1\) transits to a turbulent flow after passing the bogie section (\(2\)) and finally becomes a fully developed turbulent flow on the leeward of \(3\). In the cross sections leeward of the second car, the mean velocity at the plane of symmetry (16 mm distant from the bottom of the vehicle) is only 64 % to 69 % of the main flow. In the real condition, the relative velocity to the vehicle at the ground should be equal to the main flow speed. Although the flow around the first bogie section of the first car is similar to the real condition, the thickness of the boundary layer grows larger downstream and the velocity profile is different from that of the real case. In order to evaluate the products of turbulence at the bogie sections, all sections are covered smoothly with flat plates. In such a case, the mean velocity is as high as 80 % of the main flow.

The velocity profiles over the train roof are also measured with a hot wire anemometer. The position of the cross section in the x-direction is set at 4, 10 and 16 mm from the bottom of the model. The upper chart of Fig. 3 shows the profile of mean velocity, and the lower one shows the profile of turbulence level. The laminar flow at \(1\) transits to a turbulent flow after passing the bogie section (\(2\)) and finally becomes a fully developed turbulent flow on the leeward of \(3\). In the cross sections leeward of the second car, the mean velocity at the plane of symmetry (16 mm distant from the bottom of the vehicle) is only 64 % to 69 % of the main flow. In the real condition, the relative velocity to the vehicle at the ground should be equal to the main flow speed. Although the flow around the first bogie section of the first car is similar to the real condition, the thickness of the boundary layer grows larger downstream and the velocity profile is different from that of the real case. In order to evaluate the products of turbulence at the bogie sections, all sections are covered smoothly with flat plates. In such a case, the mean velocity is as high as 80 % of the main flow.

The velocity profiles over the train roof are also measured with a hot wire anemometer. The position of the cross section in the x-direction is the center of each car (\(1, 5, 6, 7, 8\) in Fig. 1). The z-position of the anemometer is also fixed at the center of models, and the distance from the roof is 5, 10, 15, 20, 25, 35, 45, 55 and 65 mm. Fig. 4 shows the profiles of mean velocity and turbulence level of the flow over the train. As the turbulence boundary layer goes downstream, its thickness becomes larger. However, the flow speed at 15 mm from the roof remains 90 % of the main flow, which is higher than the flow speed underneath the vehicle.

The empirical equation of the velocity profile of the turbulent boundary layer, which develops along the plane plate without a pressure gradient, is given as
if Reynolds number $R_e = \frac{U_\infty x_f}{\nu} = 5 \times 10^5 \sim 10^7$. The thickness $\delta$ of the boundary layer is obtained by substituting the equation (1) into the momentum equation of flow and integrating perpendicularly to the plate:

$$
\delta = 0.37 \left( \frac{U_\infty x_f}{\nu} \right)^{\frac{1}{3}} x_f \tag{2}
$$

where $x_f$ and $y_f$ are the distances along and perpendicular to the plate, respectively. The velocity profile over the train at the center of the five cars is approximately identical with that expressed by the equation(1) if $n$ is set at 8.

### 2.2 Measurement of sound with a parabola apparatus

In order to elucidate the mechanism of aeroacoustic noise and find ways to reduce such noise, the noises from several combinations of front shapes, bogie conditions and inter-car gaps are measured with a directional measuring device consisting of a microphone with a paraboloidal reflector (parabola apparatus). A parabola apparatus excludes the influence of back ground noise of the wind tunnel and catches only the sound from the aimed part. The measurement point of the apparatus shifts downstream when the convective effect of the sound by the high speed flow is considered. Figure 5 shows a schematic diagram of the parabola apparatus and models. In this paper, raw data acquired by the parabola apparatus are used, and the effect of directivity of the apparatus and conversion to the actual scale is not considered.

Figure 6 compares the 1/3-octave band sound pressure level with different front shapes (with all bogie sections covered smoothly with flat plates). The snow plough...
generates high-frequency noise (over 2 kHz in the model scale). Figure 7 shows the case where bogies are covered with side covers. Although the sound generated by the snow plough is still dominant in the high frequency region, its noise is masked by the noise from the bogie, especially at low frequencies.

Figure 8 and 9 show a comparison under different bogie conditions. Figure 8 shows the result at the front bogie section of the lead car, and Fig. 9 at the front bogie section of the second car. Table 1 explains each bogie condition in detail. When compared with the result under the flat condition, the others generate loud sound from 500 Hz to 16 kHz. This implies that the vortices generated by the flow separated at the upstream edge of the bogie section cause low-frequency aeroacoustic noise. The spectrum of the sound pressure level over 2 kHz differs by the existence of wheels. Figure 10 shows the effect of wheels (only this result is obtained by the test with 1/12.5 scale mirror image models). Dummy wheels are placed on the flat plate that covers the bogie section. This result indicates that high-frequency sound over 2 kHz is generated by wheels, while low-frequency sound, which cannot totally be reduced by noise barriers, is generated by the separated flow mentioned above.

Figure 11 shows a schematic diagram of the inter-car hoods. Figure 12 shows a comparison of 1/3-octave band sound pressure level with those under different conditions of inter-car gaps between the first and second cars. If hoods exist, the sound pressure level over 1 kHz far ex-

<table>
<thead>
<tr>
<th>Table 1 List of bogie conditions</th>
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<tr>
<td>Abbreviation</td>
</tr>
<tr>
<td>Flat</td>
</tr>
<tr>
<td>No bottom cover + Side cover</td>
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<tr>
<td>Bogie + No side cover</td>
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<td>Bogie + Side cover</td>
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Fig. 8 Comparison with different bogie conditions (at front bogie of lead car)

Fig. 9 Comparison with different bogie conditions (at front bogie of second car)

Fig. 10 Effect of wheels (1/12.5 scale model)

Fig. 11 Schematic diagram of the inter-car hoods

Fig. 12 Comparison with different inter-car gap conditions
ceeds that with smoothened gaps. There is a discrete peak at 1.6 kHz band when the gap is covered by inner hoods, outer hoods and snow protection hoods. The frequency of this discrete peak does not depend on the flow velocity, as shown in Fig. 13. This tone must be generated by the resonance at the closed cavity space that is surrounded by hoods.

3. Computational Results

Computational Fluid Dynamics is adopted to simulate the mechanism of the unsteady flow at the bogie section and evaluate the validity of the mirror image method. Two-dimensional incompressible Navier-Stokes equations are solved without using a turbulence model\(^4\). The Navier-Stokes solver (Modified MAC scheme) is based on a third-order upwind scheme for the convection terms and a second-order Adams-Bashforth scheme for the time marching. Non-slip boundary conditions are applied to all solid surfaces. The boundary condition on the upstream site is a uniform flow and the downstream site is set so the first derivative of pressure and velocities are at zero. If the length of the bogie section (0.16 m) is chosen as the representative length, the Reynolds Number at 300 km/h (83.3 m/s) is \(9.1 \times 10^5\).

Figure 14 shows the results of CFD that simulates the mirror image method and the real relative movement of the ground. These results indicate that if the laminar flow comes to the bogie section, the mirror image method effectively simulates the real condition because the generation of vortices is almost the same in the two flows in Fig. 14. Vortices are released from the shear layer as instability grows, then they travel leeward at the convective flow speed and impinge upon the trailing edge of the section. It seems that the sound is radiated at that instant.

4. Concluding Remarks

The aeroacoustic sound from lower parts of the train is confirmed to be generated mainly at bogie sections. Measurements of flow properties and computational results show that vortices released from the shear layer impinge upon the trailing edge of the section and radiate the low-frequency sound.

As the ratio of length to depth is about 5, the bogie section is classified as a shallow cavity\(^2\). The reason why the noise from the front bogie section of the lead car is larger than that from other bogie sections is:
(1) The wind velocity is larger compared with that at leeward bogie sections.
(2) The flow that comes to the section is laminar and the instability of shear layer grows to cause large pressure fluctuations\(^3\).

The tones of discrete frequencies at the inter-car gaps are generated by the resonance at deep cavities.

The concavities like bogie sections, inter-car gaps and gaps at doors sometimes cause unexpectedly strong noise. Measures to reduce the aeroacoustic noise have been mostly to smoothen irregularities or install covers to prevent the separation of flow. In order to reduce the noise from high-speed trains in the future, it is required to adopt new designs based on the deep knowledge of aeroacoustics acquired from wind tunnel tests and CFD.

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References

1) Takaishi, T., Zenda, Y. and Shimizu, Y.: "Wind tunnel tests for reducing aeroacoustic noise from high-speed trains," WCRR proceedings, 1999

Fig. 13 Velocity dependence of the sound from inter-car gaps (Inner and outer hood + Snow protection hood)

Fig. 14 Contour of vorticity

(a) Mirror image method
(b) Real relative movement of the ground