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AERODYNAMIC NOISE GENERATED BY SHINKANSEN CARS

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The noise value (*A*-weighted sound pressure level, SLOW) generated by Shinkansen trains, now running at 220–300 km/h, should be less than 75 dB(A) at the trackside. Shinkansen noise, such as rolling noise, concrete support structure noise, and aerodynamic noise are generated by various parts of Shinkansen trains. Among these aerodynamic noise is important because it is the major contribution to the noise generated by the coaches running at high speed. In order to reduce the aerodynamic noise, a number of improvements to coaches have been made. As a result, the aerodynamic noise has been reduced, but it still remains significant. In addition, some aerodynamic noise generated from the lower parts of cars remains. In order to investigate the contributions of these noises, a method of analyzing Shinkansen noise has been developed and applied to the measured data of Shinkansen noise at speeds between 120 and 315 km/h. As a result, the following conclusions have been drawn: (1) Aerodynamic noise generated from the upper parts of cars was reduced considerably by smoothing car surfaces. (2) Aerodynamic noise generated from the lower parts of cars has a major influence upon the wayside noise.

1. INTRODUCTION

The environmental quality standard for the noise of the Japanese Shinkansen super-express train prescribes that the maximum *A*-weighted sound pressure level, SLOW, (here refered to as the "noise value") shall be less than 75 dB(A) at the side of tracks. The current noise value at the side of tracks at a distance of 25 m laterally from the centerline between tracks and at a height of 1·2 m above the ground (the "P25" location) complies with the standard when Shinkansen trains run at 220–300 km/h. However, if the running speed of Shinkansen trains increases in the near future in order to increase the traffic efficiency, the noise value will be above 75 dB(A). Therefore, our investigations must continue to reduce the noise generated by Shinkansen cars.

In order to carry out effective countermeasures against future Shinkansen noise the noise sources must be located and the contribution to the ovrall noise level of these sources must be determined. After Shinkansen trains first came into service, the noise sources could be easily located. The main components of Shinkansen

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noise were rolling noise and steel bridge noise. The noise from these sources could easily be reduced by means of various countermeasures. However, it is becoming more difficult to quantify sources, and a method of analyzing Shinkansen noise has been developed, and the contributions of various noise sources estimated. In this method, Shinkansen noise is divided into four components as follows, and the contribution of each component to the overall noise value is estimated. [1].

(1) Noise generated from the lower parts of cars ("Lower-part noise")
  - Rolling noise, gear noise, and aerodynamic noise
(2) Pantograph aerodynamic noise
  - Aerodynamic noise generated from pantographs and pantograph shields
(3) Aerodynamic noise generated from the upper parts of cars ("Upper-part noise")
  - Aerodynamic noise generated at electric insulators, gaps between cars, louvre intakes for air conditioners, and uneven car surfaces
(4) Concrete support structure noise
  - Noise generated by the vibration of concrete bridges

The method is based on data measured with a microphone array located at P25, two microphones located under the concrete bridge structure, and at P2 (a point located at a distance of 2 m laterally from the rail, and at a height of 0·45 m above the rail head) [2].

Using this method, the transition of the contributions of various noise components to the noise value at P25 was estimated. The results are shown in Figure 1. It is found that, even after noise barriers were constructed along Shinkansen tracks in the 1970s, the rolling noise still remained to be the main source of Shinkansen noise together with spark noise (Figure 1(A)). In the early 1980s, the technique of grinding rail surfaces reduced the rolling noise by more than 5 dB(A) (Figure 1(B)), and the "bus" method eliminated the spark noise (Figure 1(C)). After that, aerodynamic noise became the most dominant contribution to Shinkansen noise. Aerodynamic noise is generated by vortex shedding from certain configurations or edges on the surfaces of Shinkansen cars, such as pantographs, louvre intakes of air conditioners, electric insulators, and gaps between cars. When Shinkansen trains increased their speed in the late 1980s, aerodynamic noise had even greater influence on the noise level (Figure 1(D)), because the power of aerodynamic noise increases in proportion to the sixth power of train speed. In order to reduce aerodynamic noise, some improvements were made to Shinkansen cars. The improvements included pantograph shields, which reduced the pantograph aerodynamic noise by about 5 dB(A) (Figure 1(E)). Nevertheless, aerodynamic noise still remained as a major component. In the 1990s, new Shinkansen trains started running at 270 km/h. The smooth surfaces of these cars reduced the aerodynamic noise by more than 5 dB(A) (Figure 1(F, G)). Today Shinkansen trains are running at 300 km/h, and aerodynamic noise has been further reduced to some extent by replacing conventional pantographs with T-shaped pantographs and removing electric insulators to further smooth the car surfaces (Figure 1(H, I)).

Now, it is necessary to define the types of noise source which should be reduced for a further reduction of Shinkansen noise. Figure 1 (I, I′) shows that pantograph

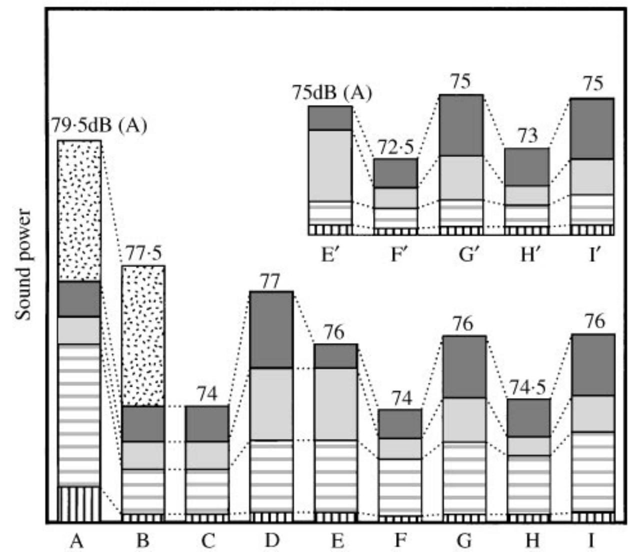

Figure 1. The noise value of Shinkansen cars measured at the point (P25). Track condition is slab. Structure condition is concrete bridges of 7–9 m in height. Noise barriers are plain barriers, 2 m in height (A–I), and inverted-L-type barriers, 2 m in height (E′–I′): ■, Spark Noise; □, Pantograph Aerodynamic Noise; ■, Upper-part noise; □, Lower-part noise; □, Concrete Structure Noise. 1982 ∼ A → B Grinding rail head (210 km/h), 1985 ∼ B → C Connecting plural pantographs with an electric wire, 1985 ∼ C → D Speed up (210 → 240 km/h), 1986 ∼ D → E Pantograph Shields, 1992 ∼ E → F Smoothing car surfaces, 1992 ∼ F → G Speed up (240 → 270 km/h), 1992 ∼ G → H Low noise pantograph Smoothening car surfaces, 1997 ∼ H → I Speed up (270 → 300 km/h).

aerodynamic noise is one of the most important noise sources at 300 km/h. If the speed of Shinkansen increases, the pantograph aerodynamic noise will become even more important. Nevertheless, this does not mean that it is sufficient to control only the pantograph aerodynamic noise in order to reduce the overall noise level. According to analysis, even at 350 km/h, for slab tacks with noise barriers noises other than the pantograph aerodynamic noise (here referred to as the “Q-noise”) have greater contribution to the noise level than the pantograph aerodynamic noise. Therefore, in order to reduce the noise level in the future, it is necessary to control not only the pantograph aerodynamic noise but also the Q-noise.

The Q-noise can be observed in the time history measured with the microphone array as noise peaks which does not correspond to the passage of the pantographs (see Figure 2); these peaks are referred to here as the “Q-level”. The sources of the Q-noise consist of upper-part noise, concrete support structure noise, and lower-part noise such as rolling noise, gear noise, and aerodynamic noise. Though the Q-noise has been isolated by use of the previous methods, the details of the distribution between individual components of the Q-noise are not clear. In this paper, a more detailed analysis is described in order to achieve a more refined analysis of the components of the Q-noise on the basis of spectrum analysis of the data measured with the microphone array at P25, with a microphone at P2, and the rail vibration. Initilly, the technique to estimate the contributions of two noises distributed in the vertical direction (that is, the upper-part noise and the lower-part

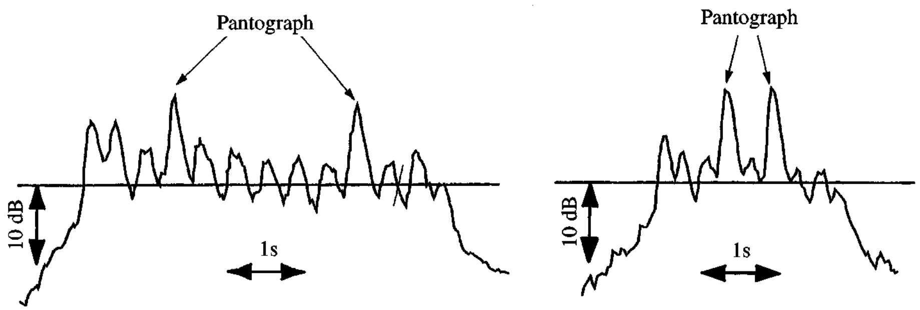

Figure 2. The time history of A-weighted sound pressure level measured with a microphone array at P25 (time constant = 35 ms): (a) S1-train (train speed = 235 km/h); (b) S2-train (train speed = 312 km/h).

noise) is described. Next, the lower-part noise is divided into three components, e.g., rolling noise, gear noise, and aerodynamic noise. Finally, some results of wind tunnel tests are shown to demonstrate the mechanism of aerodynamic noise generated from the lower parts of cars.

2. TECHNIQUE TO DIVIDE Q-NOISE

2.1. ESTIMATION METHOD

Initially, an attempt is made to estimate the contributions of two components, (upper-part noise and lower-part noise). Here, the contribution of concrete structure noise is neglected because it is normally small, in particular for ballast tracks with ballast mats. For this purpose, a technique to divide Q-noise into these two components has been developed. This technique is based on the following assumptions.

(a) The noise measured at the railside (close to the rail) includes only lower-part noise.
(b) When Shinkansen cars with fully smoothed surfaces run at a low speed (say, below 180 km/h), upper-part noise is negligible compared to other noises.
(c) The difference between the contribution at the wayside of lower-part noise and the noise level at the railside depends only upon the frequency. That is to say, the effects of noise barriers are always constant for one-frequency band.

If these assumptions are correct, Q-noise can be divided into two components by the following procedures.

(1) At first, Shinkansen noise was measured simultaneously with a microphone at P2 and a microphone array at P25 when Shinkansen trains were run at a low speed.
(2) From the measured data of Shinkansen noise at a low speed, the difference, $L_1(f)$ (*f denotes frequency*), between Q-level and the noise level at P2 for each one-third octave band frequency was obtained. $L_1(f)$ means the attenuation of

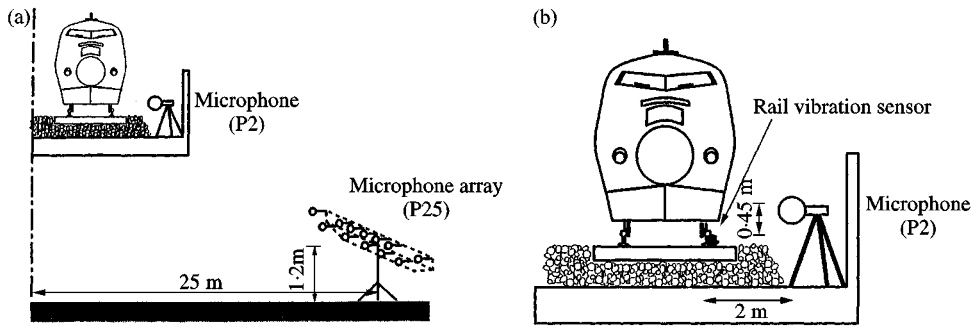

Figure 3. Diagram showing the measuring point: (a) wayside; (b) railside.

lower-part noise in propagating from P2 to P25, including the effects of noise barriers.

(3) When $L_1(f)$ is obtained, the spectrum at P25 of lower-part noise ($L_q(f)$) can be calculated at arbitrary train speeds from equation (1), by using the spectrum of the noise measured at P2 ($L_s(f)$).

$$L_q(f) = L_s(f) - L_1(f). \tag{1}$$

(4) The spectrum of upper-part noise can be obtained by subtracting, $L_q(f)$ in terms of energy from the spectrum of Q-noise.

2.2. RESULTS

By means of the technique referred in section 2.1, the Q-noise of an S3-train and an S4-train at about 300 km/h was estimated. Both of these Shinkansen cars are newly developed and have fully smoothed car surfaces. We measured the noise with a microphone at P2 and a microphone array at P25 simultaneously (see Figure 3), and obtained the spectra of the noise measured at both positions, for Shinkansen trains running at speeds of 170 and 285 km/h (for S3-train) and 300 km/h (for S4-train). The measuring sections are described as follows.

- Elevated concrete bridge structure 9 m above the ground
- Ballast tracks with ballast mats (i.e., structure noise is assumed negligible)
- Plain noise barriers 1·2 m above the rail head

$L_1(f)$ was estimated by using the spectrum of the noise at 170 km/h (for S3-train). (see Figure 4). Figure 5 shows the results of the test with an S3-train. It is found that, although aerodynamic noise is generated from the upper parts of coaches at 400–1600 Hz, it has little contribution to the Q-level even for the front cars. Figure 6 shows the results of the test with an S4-train. The Q-level is higher than the noise level of $L_q(f)$ at 500–2000 Hz. This indicates that aerodynamic noise generated from the upper parts of coaches at these frequencies dominates the level at P25. This aerodynamic noise is more noticeable for the front cars than

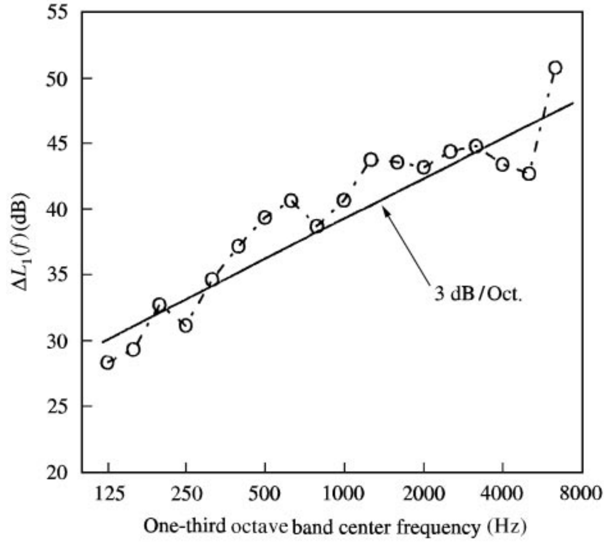

Figure 4. Relationship between $L_1(f)$ and frequency.

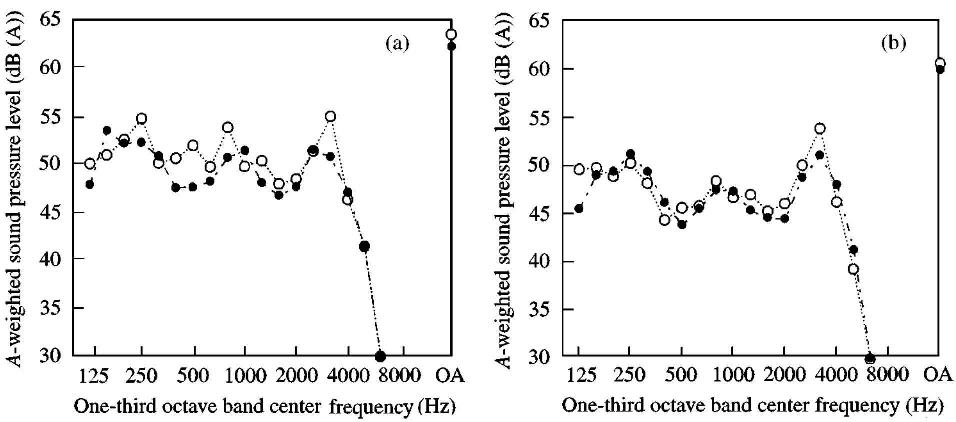

Figure 5. The spectra of Q-noise and lower-part noise at P25 '(S3-train, train speed = 285 km/h, ballast track): (a) fore cars; (b) aft car; ○, Q-level; ●, $L_q(f)$.

for the rear cars. It has little contribution to Q-level for the rear cars. This is because the boundary layer of the airflow on the rear cars is thicker than that on the front cars.

Next, the overall noise level of $L_q(f)$ was calculated, and both the contributions of the lower-part noise and the upper-part noise to the Q-level was estimated. When Figure 6 was reviewed, however, it was found that the noise level of $L_q(f)$ exceeded the Q-level in some bands (especially in the range of 125–250 Hz). In these cases, it was assumed that $L_q(f)$ = (Q-level at the same band). Table 1 shows the contribution of each component to the Q-level.

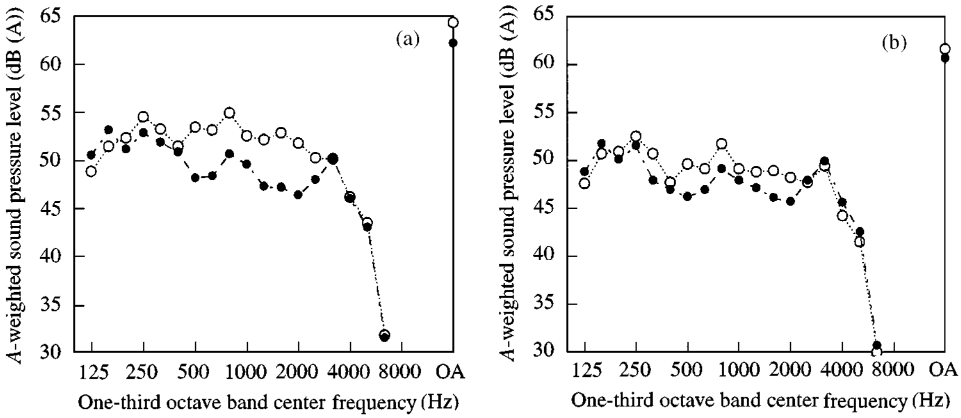

Figure 6. The spectra of Q-noise and lower-part noise at P25 (S4-train, train speed = 300 km/h, ballast track): (a) fore cars; (b) aft cars; ○, Q-level; ●, $L_q(f)$.

TABLE 1

Estimated contribution of each component to Q-level (S3-train),

	Q-level	Lower-party noise	Upper-part noise
Fore cars	63·5 dB(A)	62·0 dB(A)	59·0 dB(A)
Aft cars	61·0 dB(A)	59·5 dB(A)	54·5 dB(A)

These results mean that, except at connections near the leading car, the contribution of the upper-part noise is much smaller than that of the lower-part noise, and, even if it were to vanish completely, the Q-level would be reduced by only about 1 dB. We conclude that the upper-part noise has been reduced considerably by smoothing the car surfaces, and that major noise sources at the wayside are lower-part noise and pantograph aerodynamic noise.

3. NOISE GENERATED FROM THE LOWER PARTS OF CARS

3.1. ESTIMATION METHOD

It was concluded in section 2 that lower-part noise made major contribution to the noise level at the wayside. Lower-part noise consists of rolling noise, gear noise, and aerodynamic noise. In this section, a method to divide lower-part noise into the three components is shown. The method of estimating the contribution of each component is as follows.

(1) The rail vibration and the noise at P2 is measured when a Shinkansen train runs at a low speed (say, below 180 km/h). At this speed, the major noise source is the rolling noise, and rolling noise is mainly radiated by the rail [1].

(2) From the data measured at a low speed, the difference, $L_2(f)$, between the rail vibration velocity level and the noise level at P2 for each one-third octave band frequency can be obtained.
(3) When $L_2(f)$ is obtained, the spectrum at P2 of the rolling noise ($L_r(f)$) at arbitrary train speeds can be calculated from equation (2), by using the spectrum of the rail vibration velocity ($L_v(f)$).

$$L_r(f) = L_v(f) - L_2(f). \tag{2}$$

(4) Gear noise has a distinct gearing frequency (at constant speed), and the noise level in the one-third octave band corresponding to the gearing frequency can be considered to be the contribution of the gear noise.
(5) After subtracting in terms of energy the spectra of the rolling noise and the gear noise from the spectrum of the noise at P2, the spectrum of the aerodynamic noise is obtained.

3.2. RESULTS

By means of the technique mentioned in section 3.1, the lower-part noise of an S5-train was divided into three components at 315 km/h. In addition, the rail vibration and Shinkansen noise at P2 (see Figure 3) when the new S5-train ran at 150 and 315 km/h, was measured and the spectra were obtained. The measuring sections are described as follows.

- Elevated concrete bridge structure 9·5 m above the ground.
- Ballast tracks with ballast mats.
- Plain noise barriers 2 m above the rail head

Figure 7 shows the spectra of the rail vibration velocity and the noise measured at P2 when the S5-train ran at 150 km/h. Figure 7 also shows the spectrum of rolling noise at 315 km/h estimated by the method described in section 3.1. In the frequency range of 100–500 Hz, the estimated rolling noise is about 10 dB lower than the noise at P2. The gearing frequency was in the 2000 Hz band at 315 km/h. This result indicates that the noise, except the rolling noise and the gear noise, is radiated from the lower parts of cars.

The dependence of the rail vibration velocity level and the noise level at P2 upon train speeds is now considered. It appears that, at 100–500 Hz, the rail vibration velocity level increases approximately in proportion to the third power of train speeds, whereas the noise level increases approximately in proportion to the sixth power. It can be deduced that the noise in the frequency range of 100–500 Hz at high speeds was primarily an aerodynamic noise.

At the railside, the aerodynamic noise made a much smaller contribution than the rolling noise. However, the attenuation effects of the noise barriers tends to increase as the frequencies increase (see Figure 4), and, if the frequency of the aerodynamic noise is lower than that of rolling noise is taken into account, the contribution of the aerodynamic noise at the wayside can be no longer be ignored. In fact, inspection of the spectrum of lower-part-noise at P25 (see Figure 5), shows

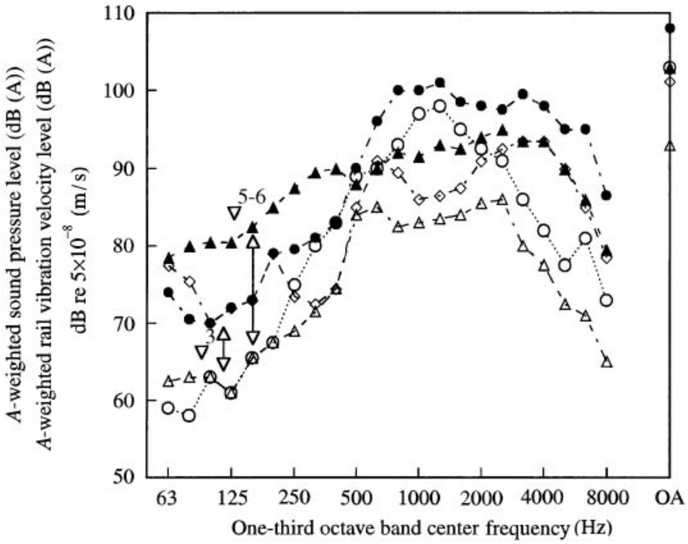

Figure 7. The spectra of the rail vibration velocity, the noise measured at P2, and the rolling noise (S5-train, ballast track). ○, rail vibration (train speed = 150 km/h); ●, rail vibration (train speed = 315 km/h); △, noise (train speed = 150 km/h); ▲, noise (train speed = 315 km/h); ◇, rolling noise (train speed = 315 km/h).

that the noise level at 125–500 Hz is almost equal to that at 630–2000 Hz. Therefore, the contribution of the aerodynamic noise to the noise at the wayside is estimated to be comparable to that of rolling noise.

4. WIND TUNNEL TEST

In order to investigate the characteristics of aerodynamic noise, wind tunnel tests have for some years been carried out with scaled models. In this study, wind tunnel tests on the aerodynamic noise generated from the lower parts of cars were conducted.

4.1. LARGE-SCALED LOW-NOISE WIND TUNNEL

The Railway Technical Research Institute has constructed a large-scale low-noise wind tunnel at Maihara, Japan which has a maximum flow velocity of 400 km/h. The background noise value of this wind tunnel is 75 dB(A) at 300 km/h under open-jet conditions (measuring point: 4·5 m away from the center of the nozzle, 3 m downstream of the nozzle). The dimensions and main features of this wind tunnel are shown in Table 2.

4.2. FLOW PROFILE UNDER THE CAR BODY

A 1/5-scaled model of Shinkansen cars (here refered to as the “scaled model”) was tested in the wind tunnel. The flow profile with the scaled model must be similar to

TABLE 2

The parameters, dimensions and main features of wind tunnel

Items	Specification	
Tunnel	Gottingen-type single return tunnel	
Test section	Open type	Close type
Width and height	3·0 m(W) * 2·5 m(H)	5·0 m(W) * 3·0 m(H)
Length	8 m	20 m
Maximum flow velocity	400 km/h	300 km/h
Background noise level	75 dB(A) at 300 km/h	
Accessory	Anechoic room	Moving ground belt

that with real Shinkansen cars in order to make the noise generated from the scaled model correspond to that from real Shinkansen cars. For this purpose, two techniques for wind tunnel tests have been used; the moving-ground belt technique [3] and the image technique. However, there are some problems making acoustic measurements with both techniques. In the case of the moving-ground belt technique, it is difficult to estimate the noise generated from the scaled model only, because the noise radiated from the moving belt itself is included in the noise measured. In the case of the image technique, the scale of models necessarily is very small since two scaled models are required. Therefore, it is difficult to estimate the contribution of the aerodynamic noise generated by each part of the scaled models. Therefore, the technique of arranging the scaled model to attain the flow field relevent to real Shinkansen cars without using the moving-ground belt was investigated. In order to investigate this technique, three conditions with different distances between the scaled model and the ground were tested. The conditions were as follows.

The distance between the scaled model and the ground is:

Condition (A): 80 mm (corresponding to 400 mm on a 1/1 scale, with the moving-ground belt)

Condition (B): 80 mm (without the moving-ground belt).

Condition (C): 160 mm (without the moving-ground belt).

Since the distance between the underside of real Shinkansen cars and the ground is 400 mm, Condition (A) is representative of the actual situation. Flow profiles were measured with pitot-tubes at two X-positions (see Figure 8).

Figure 9 shows the velocity profiles under the three conditions. In Figure 9, the flow field under Condition (C) is similar to that under Condition (A). Therefore, it is appropriate in the present tests to set-up the scaled model at twice the distance between the scaled model and the ground.

4.3. NOISE SOURCE DISTRIBUTION

The noise generated from the scaled model set up under Condition (C) was measured with a parabolic antenna (see Figure 8). The parabolic antenna has strong directivity and sensitivity, both of which depend on the frequency of incident

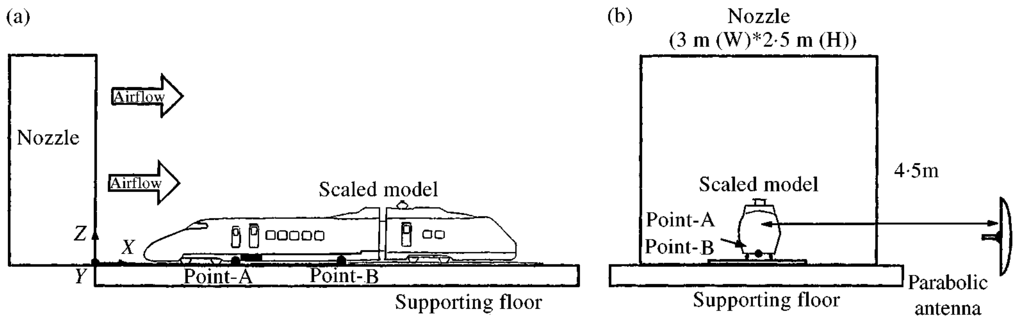

Figure 8. Diagram showing the wind tunnel test: (a) Side view; (b) Front view.

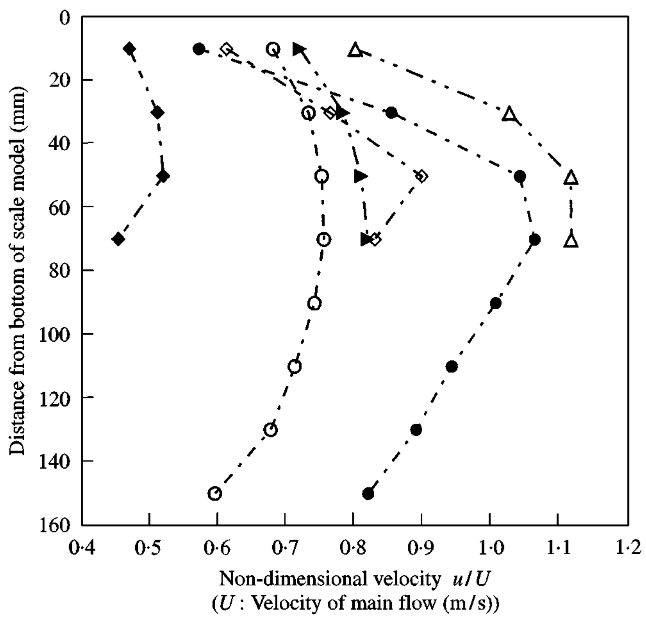

Figure 9. The flow velocity under the scaled model; △, point-A under condition (A); ◇, point-A under condition (B); ●, point-A under condition (C); ▲, point-B under condition (A); ◆, point-B under condition (B); ○, point-B under condition (C).

sound. Therefore, the data measured with the parabolic antenna has to be corrected in order to estimate the contribution of each part of real cars. The correcting procedure is as follows.

- Subtracting a gain of the parabolic antenna for each one-third octave band frequency from the data
- Shifting the frequencies ($f_{real} = f_{model}/5$)
- Making A-weighting corrections
- Calculating the overall level

Figure 10 shows the contour of the corrected noise level measured with the parabolic antenna. It is found that the aerodynamic noise is generated at a position

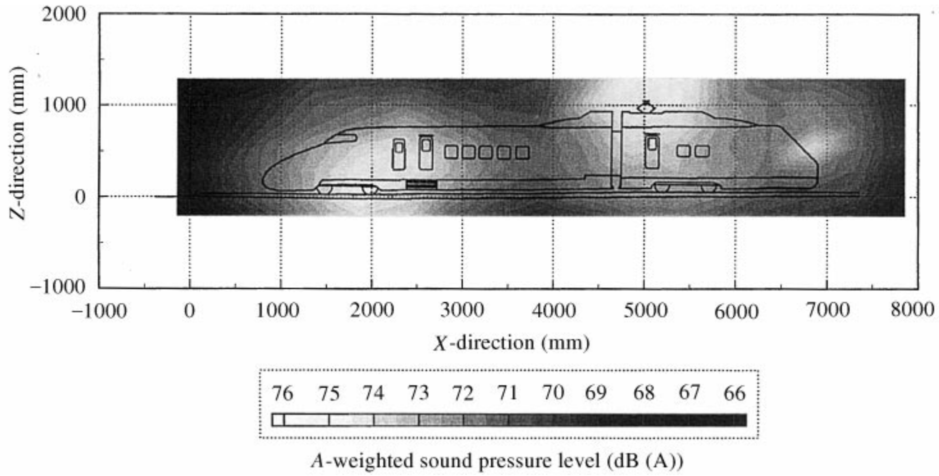

Figure 10. The contour of the noise generated by scaled model, measured with the parabola apparatus. (Flow velocity = 300 km/h).

near the bogie. The aerodynamic noise is generated at wheels, bogie, edges around the bogie and the space in which the bogie is placed. However, the noise sources are so close to each other that only rough estimates of the contribution of each noise source can be made.

5. CONCLUSIONS

In order to achieve a detailed separation of individual components of Q-noise, a technique has been developed based on a spectrum analysis of those noise sources by using the data measured with a microphone array at P25, that measured with a microphone at P2, and the rail vibration. The following results have been obtained:

- after the car's surfaces were smoothed, the upper-part noise was reduced considerably and the major noise sources at the wayside were the lower-part noise and pantograph aerodynamic noise.
- the contribution of the aerodynamic noise generated from the lower part of cars to the wayside noise level was estimated to be comparable to that of rolling noise.

Furthermore, it was found by wind tunnel tests that this aerodynamic noise was generated at a position near the bogie.

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