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ANALYSIS OF SOUND SOURCE CHARACTERISTICS OF SHINKANSEN CARS BY MEANS OF X-SHAPED MICROPHONE ARRAY

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1. INTRODUCTION

Reduction in the noise level of Japan's high-speed train Shinkansen is important for two reasons. One is the necessity to operate the trains quietly through populated arias. The other is the need to more clearly define the source distribution of the aerodynamic component of the noise, which predominates at high speeds[1]. Aerodynamic noise is dominant because rail and wheel noise is shielded by sound barriers all along the tracks, and aerodynamic noise sources such as pantographs are left unshielded[2]. Japanese environmental regulations state Shinkansen noise must be evaluated at its "slow" peak level. This means that reducing the dominant discrete sources such as pantographs will contribute more toward reducing the evaluated noise level, than will reducing the dispersed noise from rails and wheels [3][4].

This paper describes a method to measure the two dimensional noise source distribution of Shinkansen trains and their noise characteristics, and presents experimental results for an X-shaped microphone array [5][6].

2. BASIC THEORY

Non-directional M point sources, whose radiated sound pressure is $s_i(t)$ (i=1,...,M) at unit distance at time t, are assumed to be located on the surface of the vehicle. In a nondiffracted sound field, the sound pressure p_j(t) (j=1,...,N) at each microphone is expressed as in Eq. (1):

$$p_j(t) = \sum_{i=1}^{M} \left\{ s_i\left(t - \frac{r_{ij}(t)}{c}\right) \Big/ r_{ij}(t) \right\} \tag{1}$$

where

$c =$ Velocity of sound (m / s)

$p_j(t) =$ Sound pressure at j^{th} microphone (Pa)

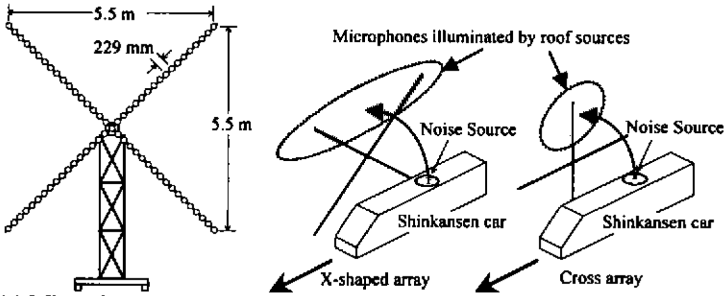
$s_i(t) =$ Sound pressure at unit distance from i^{th} point source (Pa)

$r_{ij}(t) =$ Distance from i^{th} point source to j^{th} microphone (m)

In estimating the sound source $s_i(t)$, we have assumed incoherency between noise source points on the surface of the vehicle. This assumption is valid for most of the aerodynamic noise sources which are our current interest. When the array is located close to the sound source, where the radiated wave is considered spherical, we can focus on a single target source by adjusting for the time delay caused by sound propagation, as in Eq. (2):

$$s_i(t) \approx -\left\{ \sum_{j=1}^{N} W_j p_j\left(t + \frac{r_{ij}(t)}{c}\right) \Big/ \sum_{j=1}^{N} \frac{W_j}{r_{ij}(t)} \right\} \tag{2}$$

The hamming window function, W_j is used to reduce side lobes. This imposes an unexpected effect on the array measurements.



(a) Microphone arrangement (b) Illuminated microphones

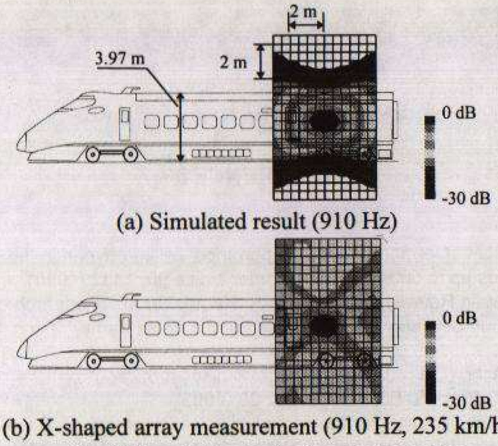
Fig. 1. X-shaped microphone array configuration.

Our two dimensional, X-shaped microphone array configuration is shown in Fig. 1(a). In the field measurement, the array was placed within a plane 6 meters away from the target vehicle, where the radiated sound wave is considered spherical. Since the array was placed close to the source, some of the microphones were located in a region of diffracted shadow from which the target source could not be tracked. Hence, we were able to get data only from the microphones in the illuminated regions. Fig. 1(b) shows a case in when the noise source was located on top of the target vehicle. The X-shaped array still had an equal number of illuminated microphones on each line array, thus yielding two-dimensional information. However, with a cross array system, if the array height is lower than the roof level, microphones on a horizontal array are in a shadow region.

3. RESULTS

Array Resolution

The resolution of the X-shaped array system was examined by a loudspeaker test using a 400-series Shinkansen car "Tsubasa". Sound at 455 Hz, with its harmonics, were radiated from a speaker located at a window, as in Fig. 2. Fig. 2(a) shows the theoretical freefield sensitivity distribution at 910 Hz for a stationary source, averaged over 20 meters along the rail. The results from measurement using the X-shaped microphone array are shown in Fig. 2(b). The measured results agree well with the theoretical free-field sensitivity around the speaker position. The equal sensitivity line for -3 dB is elliptical in shape and has a longer axis in the direction of motion, due to the movement of the source. The spacing between the microphones in each line array was 229 mm, which corresponds to the half wave length for 740 Hz. According to sampling theory, this is the highest frequency for an array system in a plane wave region. However, in the spherical wave region, it is possible to obtain reasonable results above this frequency limit.



(a) Simulated result (910 Hz)

(b) X-shaped array measurement (910 Hz, 235 km/h)

Fig. 2. Resolution test using loudspeaker

Noise Source Characteristics

Fig. 3(a) and (b) show the measured results for the high-speed experimental train STAR21, running at 254 km/h and 292 km/h, respectively. Figures show the overall value for frequency range 300 to 3 kHz. Fig. 3(c) shows the rate of increase in noise defined by Eq. (3),

$$n = \Delta L / \log(\Delta V) \tag{3}$$

where the ΔV is the increase in velocity (m/s), and ΔL is the increase in sound (dB). A typical rate of increase is 2 for the vibration-induced noise and 6 to 8 for the aerodynamic noise. From these results, the following can be inferred.

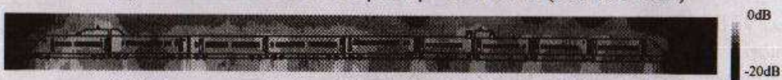
(1) The dominant noise sources of the STAR21 are the pantographs, the rails and wheels, and the coupling area.

(2) The increase rate in the noise shows that aerodynamic noise is radiated from the pantographs and the side surfaces of the cars, while vibration noise comes from the rails and wheels and the coupling area.

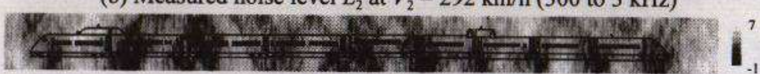
(3) There is no strongly vibrating part in the coupling area, so the noise source there is assumed to be reflected sound from rails and wheels.

(4) To the further increase of the operation speed of Shinkansen, reduction of aerodynamic pantograph noise, and reduction and shielding of rails and wheels vibration noise, is essential.

(a) Measured noise level L_1 at V_1 = 254 km/h (300 to 3 kHz)



(b) Measured noise level L_2 at V_2 = 292 km/h (300 to 3 kHz)



(c) Rate of increase n

Fig. 3 Measured noise level of STAR21

4. REFERENCES

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