Analytical Method of Noise Contribution Ratio in Railway Vehicle Using Small Speaker and Acoustic Particle Velocity Sensor

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To apply noise reduction countermeasures effectively in a railway vehicle, it is necessary to clarify the contribution ratio of each noise generation source at each noise evaluation position. The acoustic characteristics of an evaluation position in an enclosed space can be represented as the product of the acoustic particle velocity near the noise source and the acoustic transfer function between the noise source and the evaluation position. Therefore, the authors have developed a new analytical method to estimate the acoustic characteristics of an arbitrary evaluation position in a space, and the noise contribution ratio of noise sources using an acoustic particle velocity sensor and a small loudspeaker. This paper describes the outline of the method and verification results from excitation tests on a stationary test vehicle.

Keywords: interior noise, contribution ratio, acoustic particle velocity, transfer function

1. Introduction

One way to improve passenger comfort on railway vehicles is to reduce the interior noise. The interior noise, the sound radiating through the passenger room, enters the vehicle either as structure borne vibrations and sound originating from the bogies and car body, or as sound transmitted through the body structure. Those noises take complex propagation paths from their sources to the passenger room. To reduce the interior noise effectively, the first important step is to clarify the contribution ratio of each noise source, from the floor and ceiling panels and, side plates, etc. (hereafter collectively referred to as “the interior panels”), to the radiated sound at each interior noise evaluation position (sound receiving point).

Numerous analyses have been conducted over the years on railway vehicle interior noise contribution ratios [1, 2]. In recent years, however, only a small number of studies have been released in Japan that give details about the methods used. It is surmised that these analyses probably employed calculations based on the vibration of the interior panels measured with acceleration sensors and other tools, the sound pressure at the sound receiving point and the related vibration propagation characteristics. It is also presumed that numerical analysis techniques on acoustics based on boundary elements and other methods using detailed interior vibration data were used. Those methods, however, appear challenging, with the former being required to establish a clear relationship between the interior panels’ vibration and radiated sound and the sound receiving point’s acoustic characteristics, and the latter requiring tremendous effort to conduct the numerical analysis.

Given the above, the authors have developed a simplified analysis method to clarify contribution ratio to the interior noise. The method takes the following steps: using a recently developed acoustic particle velocity sensor, acoustic particle velocity is first measured directly in close proximity to the interior panels in a vehicle running environment, and then again in a stationary setup in which sound is emitted from a small speaker: a transfer function between the interior panels and sound receiving point is obtained through calculations. Finally, the results of these steps are combined to clarify the interior noise contribution ratio. This paper presents the outline of the simplified method and the results of a stationary test vehicle excitation test to verify the method.

2. Outline of the interior noise contribution ratio analysis method

2.1 Basic principles [3, 4]

A walled-in space (shown in Fig. 1) is used that is similar to the passenger room in a railway vehicle. When the wall surfaces are vibrating, radiating sound into the space, the radiated sound from the wall surfaces (sound sources) in the frequency domain can be obtained by, as shown in Fig. 1 and by (1), integrating the product of the acoustic particle velocity at the sound source surfaces and the transfer function representing the space’s sound propagation characteristics in the area domain of the sound source surfaces [5].

\[ p(r) = \int_{S_0} G(x | r) v(x) dS \]  

where: \( p(r) \) is the sound pressure at position \( r \) (sound receiving point) in the space, \( S_0 \) is the surface domain of the sound source, \( G(x | r) \) is a Green function corresponding to the transfer function from the sound source surface posi-
the angular frequency and particle velocity at the sound source surface position. A small area of the sound source, directivity, the acoustic particle velocity sensor, not easily receiving point can be obtained by taking the following three steps:

(i) Measure the acoustic particle velocity $\mathbf{v}(x)$ at the sound source surface (normally measured in a vehicle running state but in this paper measured in a stationary vehicle excitation state).

(ii) Calculate the transfer function $G(x|\mathbf{r})$ between the measuring and sound receiving points of (i) (the acoustic particle velocity and sound pressure measured and calculated in a stationary state).

(iii) Integrate the product of the values from (i) and (ii) in the sound source surface area domain.

### 2.2 Measurement of acoustic particle velocity

Acceleration sensors were typically used to measure acoustic particle velocity: an acceleration sensor was attached to the surface of a sound source and the measured acceleration was integrated for conversion to acoustic particle velocity. An acoustic particle velocity sensor (shown in Fig. 2) was recently developed by Microflown Technologies of the Netherlands, that is capable of directly measuring acoustic particle velocity by sensing acoustic energy-induced vibrations based on the same principle as a hot-wire anemometer [6, 7]. With its figure-8 bi-directional spatial directivity, the acoustic particle velocity sensor, not easily influenced by surrounding sound, offers highly accurate acoustic particle velocity measurement. In the simplified analysis method presented in this paper, acoustic particle velocity is measured from one measurement point to another over the entire surface of the sound source using an acoustic particle velocity sensor. Acoustic particle velocity at each measurement point is obtained as a complex vector taking into account the phase differences from the other measurement points.

### 2.3 Calculation of transfer function

The transfer function $G(x|\mathbf{r})$ between the measurement and sound receiving points can be regarded and obtained as a frequency response function representing the sound propagation characteristics of the sound receiving point to the acoustic particle velocity in a small area of the sound source surface position. In reality, however, it is difficult to measure those characteristics, specifically with respect to the acoustic particle velocity of a small area only, as the entire sound source vibrates. On this, a method has been proposed which relies on reciprocity theorems of sound characteristics, whereby a speaker is installed at the sound receiving point to radiate sound, and the acoustic particle velocity and sound pressure at the sound source surface position are measured to obtain the transfer function [8]. In our simplified analysis method, a small low-profile speaker was installed on the sound source surface to radiate sound, and a transfer function from the sound source position forward to the sound receiving point was obtained. At each of the acoustic particle velocity measurement points mentioned in 2.2, a transfer function was calculated as a complex number.

### 2.4 Estimation of sound characteristics at the sound receiving point

Here, a process is considered to obtain sound pressure as the acoustic characteristics at a sound receiving point. As (1) indicates, sound pressure at a sound receiving point can be obtained by integrating the product of the acoustic particle velocity on the sound source surface discussed in 2.2 and the transfer function discussed in 2.3 in the area domain of the sound source surface. As acoustic particle velocity and transfer function are normally measured discretely, (1) can be converted into the following equation.

$$p(r) = \frac{1}{2} \frac{j \rho_0 c_0}{\omega} \sum \Delta S(x_n) G(x_n|\mathbf{r}) \mathbf{v}(x_n)$$

where: $N$ is the number of divided segments of the sound source surface and $\Delta S(x_n)$ is the small area at position $x_n$. The transfer function $G(x_n|\mathbf{r})$ can be described as follows.

$$G(x_n|\mathbf{r}) = \frac{p'(r)}{v'(x_n)}$$

where: $v'(x_n)$ is the acoustic particle velocity of the sound radiating from the small speaker and $p'(r)$ is the corresponding sound pressure at the sound receiving point. This indicates that, with the space used in transfer function measurement having linear sound propagation characteristics, the acoustic particle velocity of the sound from the small speaker does not have to be equal to the acoustic particle velocity measured at the sound source surface.
2.5 Calculation of contribution ratio

Figure 3 outlines the concept of the calculation method presented in this paper to find the contribution ratios. The figure shows vectors of the pressures at the sound receiving point of the sounds from the sources 1 and 2 and the sound pressure at the sound receiving point, shown on a complex plane while focusing on a specific frequency. In the simplified analysis method presented here, the sound pressure contribution ratio measured at the sound receiving point from each sound source position is defined as the ratio of the vector component of sound pressure from each sound source to the direction of the vector of the sound pressure at the sound receiving point. This can be expressed in (4).

\[ C_i = \frac{p_i(r) \cos \theta_i}{p(r)} \]  \hspace{1cm} (4)

where: \( C_i \) is the contribution ratio of the \( i \)-th sound source, \( p(r) \) is the synthetic vector of the sound receiving point’s sound pressure, \( p_i(r) \) is the vector of the sound pressure from the \( i \)-th sound source, and \( \theta_i \) is the angle of the vector \( p_i(r) \) of the sound pressure at the sound receiving point and the vector \( p(r) \) of the sound pressure from the \( i \)-th sound source. The vector \( p(r) \) of sound pressure from each sound source acts to increase the sound pressure vector at the sound receiving point when \( -\pi/2 < \theta_i < \pi/2 \), making “positive contribution ratio” and therefore offering a positive \( C_i \). On the other hand, when \( \pi/2 < \theta_i < 3\pi/2 \), it acts to decrease the sound pressure vector at the sound receiving point, making “negative contribution ratio” and therefore offering a negative \( C_i \).

Classifying contribution ratios as either positive or negative makes it possible to determine which sound source is cancelling out the sound at the sound receiving point (cancellation mechanism). With this sound propagation environment, it is anticipated that contribution ratios, both positive and negative, could exceed one. In addition, with the contribution ratio defined as it is, if noise mitigation measures lead to change in the sound radiating from a certain source, the synthetic vector of sound pressure at the sound receiving point will change, necessitating the contribution ratio \( C_i \) of each sound source to be recalculated.

3. Contribution ratio analysis in stationary excitation test

3.1 Outline of the test

In an attempt to verify the simplified analysis method, a stationary excitation test was conducted on a Shinkansen-type test vehicle owned by RTRI. The interior noise generated during the test was examined to estimate the...
sound pressure characteristics and contribution ratios at two sound receiving points.

As the excitation source, an electrodynamic actuator (Asahi Seisakusyo SW-1015) was installed on the traction link bracket (on the car body) of the test vehicle to provide random-wave fore and aft excitation (Fig. 4).

As shown in Fig. 5, a microphone (RION Co., Ltd. NL-20) was installed at two locations in the second seat row of the passenger room: one at the center in the sleeper direction (sound receiving point C) and the other on the left-hand seat looking toward the deck from the center (sound receiving point L), both at 1200 mm above the floor. The acoustic particle velocity and transfer function were measured using an acoustic particle velocity sensor (Microflossn Technologies PU regular) at 45 locations in the 1st, 2nd and 3rd seat rows, i.e. in nine position each: on the floor, left-hand (LH) side, right-hand (RH) side, ceiling and end panel. Measurements were taken at three locations in each seat row for the floor and the ceiling: in the LH seat, the center aisle and the RH seat. Measurements were taken at three locations in each seat row on the LH and RH sides: at the frieze board, window and wainscot panel, all at the center. The end panel was divided into nine portions of the same area and measurements were taken at the center of each portion.

3.2 Measurement of acoustic particle velocity in close proximity to interior panels

Figure 6 shows how the acoustic particle velocity was measured in close proximity to the interior panels using an acoustic particle velocity sensor. By using the sensor, non-contact measurements can be made of the acoustic particle velocity close to vibrating interior panels.

Figure 7 shows the frequency characteristics of the acoustic particle velocities measured at the center locations on the floor, ceiling and both sides in the second seat row and at the center location of the middle level at the end panel. In the frequency range of 150 Hz and above, traction link bracket excitation generated the highest level of acoustic particle velocity close to the floor while the other locations had nearly the same levels.

3.3 Calculation of transfer function

A small monaural speaker (Princeton Ltd. PSP-BTS-3BL, hereafter “the small speaker”) was attached to each of the measurement points in Fig. 5 and, while sound was radiated in random waves from the speaker, its acoustic particle velocity was measured with an acoustic particle velocity sensor attached to the speaker in close proximity. Then, based on the measured velocities and the sound pressures at a sound receiving point, a transfer function was obtained. Figure 8 shows how the acoustic particle velocity was measured in close proximity to the small speaker. Coherence between the acoustic particle velocity in close proximity to the small speaker and the sound pressure at the sound receiving point C was examined. Figure 9 shows an outstanding coherence observed in the 100 - 300 Hz range. The strong coherence in that particular range appears to be due to the acoustic particle velocity sensor being the most sensitive at and around 180 Hz. Accordingly, verification centered around the 100 - 300 Hz range.

Figure 10 shows the transfer functions between the acoustic particle velocities at the measurement points and the sound pressures at the sound receiving point C. Figure 10 (a) shows that the sounds from the floor panels, both
sides and ceiling received at the point C had nearly the same level of magnitude while that from the end panel had a lower magnitude. As shown in Fig. 10 (b), the sounds received at the point C from the various interior panels had phase differences between them. It is presumed that those phase differences contribute to the relevant sound pressures cancelling each other out at the sound receiving point C.

### 3.4 Estimation of sound pressure at the sound receiving point

Figure 11 shows the sound pressure measured at the sound receiving point C when the traction link bracket was excited and the corresponding values estimated with the simplified analysis method. The estimated sound pressure level was achieved through multiplication for alignment in magnitude with the measured values. Of the 100 - 300 Hz range where coherent transfer functions were obtained as shown in Fig. 10, the measured and estimated values show characteristics similar to each other approximately in the 130 - 300 Hz range (indicated with a blue arrow in Fig. 11). In the remaining frequency ranges, there are gaps between those values due to less coherent transfer functions in those ranges. Reliable estimation of sound pressure at sound receiving points could be achieved if good quality acoustic particle velocity and transfer functions could be obtained across the entire frequency range.

### 3.5 Vector and contribution ratio of sound pressure at sound receiving points

As (1) indicates, the sound pressure at the sound receiving points C and L that radiates from the measurement points can be expressed as a complex number. Figure 12 shows vectors of the sound pressure at the sound receiving points and vectors of the pressure at those receiving points of the radiated sound from the measurement points, both in the 200 Hz band (1/3 octave band) on complex plane. Figure 13 and Figure 14 show the contribution ratios at the sound receiving points C and L respectively. Figure 12 (a) shows that the vector of the sound pressure at the sound receiving point C is almost identical to that of the pressure at that point of the radiated sound from the floor panel, and that the vectors of the sound pressures from the

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Fig. 9 Example of coherence between acoustic particle velocity in close proximity to the small speaker and sound pressure at sound receiving point C

Fig. 10 Transfer functions between the acoustic particle velocities at the measurement points and the sound pressures at the sound receiving point C
other measurement points were extremely small. Using (2), the measurement points' contribution ratios were calculated. The results are given in Fig. 13, showing that the floor panel had the highest contribution ratio. This is what should be expected from the acoustic particle velocities in Fig. 7 and the transfer functions in Fig. 10. The ceiling, RH side, and end panel had slightly negative contribution ratios, which suggests that the cancellation mechanism acted to lower the sound pressure at the sound receiving point C.

As for the sound pressure contribution ratios at the sound receiving point L, shown in Fig. 12 (b), effects of radiated sound from not just from the floor panel but also from the LH side are evident. In comparison with the contribution ratios at the sound receiving point C in Fig. 13, those at the sound receiving point L in Fig. 14 show the contribution ratio of the floor panel being smaller at around 0.7 while that of the LH side becoming greater at around 0.3. This appears to be due to the sound receiving point L being closer to the LH side than the sound receiving point C as shown in Fig. 5, thus more susceptible to the radiated sound from the LH side, making the contribution ratio of the floor panel relatively smaller. This also coincides with intuitive perceptions of the sound pressure characteristics of the sound receiving point L.

4. Conclusion

To effectively apply measures for interior noise reduction in railway vehicles, it is important to clarify sound pressure contribution ratios at interior noise evaluation positions. To this end, the authors developed an analysis method for clarifying those contribution ratios using a small speaker and acoustic particle velocity sensor. This method seeks to clarify contribution ratios by measuring acoustic particle velocity directly in close proximity to various locations of the interior using an acoustic particle velocity sensor and then calculating the transfer functions between those locations and the noise evaluation positions (sound receiving points) based on the radiated sound from a small speaker. In addition, the pressure of the radiated sound from various interior locations is expressed in vectors on a complex plane to provide positive and negative contribution ratios. Negative contribution ratios act to cancel out, or help reduce, sound pressure at a sound receiving point.

In an attempt to verify the method, a stationary excitation test was conducted on a Shinkansen-type test vehicle. The radiated sounds from various interior locations were examined to calculate their contribution ratios at two sound receiving points. The results showed that the floor panel, which was close to the excitation point, had significant contribution ratios and that the contribution ratio of the left-hand side was clearly reproduced at the sound receiving point, which was closer to the left-hand side than the other sound receiving point.

Going forward, the authors will make efforts to expand the applicable frequency range for the method and to verify the method on a running vehicle.

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