Study on the Application of Transfer Path Analysis to the Structure Borne Sound from the Bogies of Railway Vehicles

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ABSTRACT

It is known that the structure borne sound from the bogie largely contributes to the interior noise above the bogie. Moreover, the interior noise above the bogie has a peak in a frequency band of approximately 100–300 Hz, particularly in the case of high-speed vehicles. Hence, it is important to comprehend the transfer paths to adopt countermeasures against the interior noise caused by the structure borne sound from the bogie of railway vehicle. The purpose of this study was to apply transfer path analysis (TPA) to the structure borne sound from the bogie and to specify the contribution ratio according to the transfer paths. The study evaluated the contribution ratios by applying operational path analysis (OPA), which was one of TPA technique, to the vibration transfer paths from the bogie to the floor in running tests. The findings confirmed that OPA was effective in the structure borne sound from the bogie. It was indicated that the confirmation procedure of the validity to apply OPA to structure borne sound from the bogies. With the procedure, it revealed that it was possible to apply OPA in the frequency range of 100–300 Hz.

Keywords: Railway vehicle, Transfer Path Analysis, Structure borne sound
I-INCE Classification of Subjects Numbers: 13.4.1, 74.6

1. INTRODUCTION

Recently, various environmental concerns were raised regarding the interiors and exteriors of railway vehicles because of the increasing speed and decreasing mass of railway vehicles. Reducing the interior noise of railway vehicles to improve the comfort of passengers is an important topic. As shown in Figs. 1 and 2, the interior noise can be classified into two types, namely, structure borne sounds and transmitted sounds. The vibration of the car body generates the former sound type and it propagates from the bogie, the pantograph, and the under-floor equipments. The latter sound type is an exterior noise transmitting through the car body structure, i.e., the floor, side windows, wainscot panels, and roof. It is important to understand the transfer paths of those sounds in detail to adopt efficient noise-reduction countermeasures.

Transfer path analysis (TPA) is widely used in the automobile to clarify noise transfer paths. In this study, TPA was applied to the interior-noise transfer paths of structure borne sound from a bogie. The characteristics of the interior noise differed based on the position inside the cabin. Furthermore, the interior noise level above the bogie (the end of the cabin) was higher than that at the center of the cabin. It is known that structure borne sound from the bogie contributes greatly to the interior noise immediately above the bogie, and that this noise has a peak in the frequency band at approximately 100–300 Hz [1]. The structure borne sound from the bogies is considered to mainly propagate through the parts connecting the bogie and car body such as traction devices (for example traction links), yaw dampers, and air springs, as shown in Figs. 1 and 2.

For railway vehicles, the car body is supported by wheelsets in which the left and right wheels are rigidly attached by very stiff bogie frames that support the wheelsets. The relative independence of inputs poses a problem with respect to the traction links, the yaw dampers, and the air springs as input

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points to the car body. In the low frequency region, the rigid motion of the bogie dominates and independence may be assured only in a sufficiently high frequency region. Therefore, this study adopted operational path analysis (OPA) and specified the possible restrictions in its application to railway vehicles.

In this study, the contribution ratios were described by applying OPA to the vibration transfer paths from the bogie to the floor in high-speed railway vehicle running tests. We examined the confirmation procedure of the validity to apply OPA in the form of practical angle.

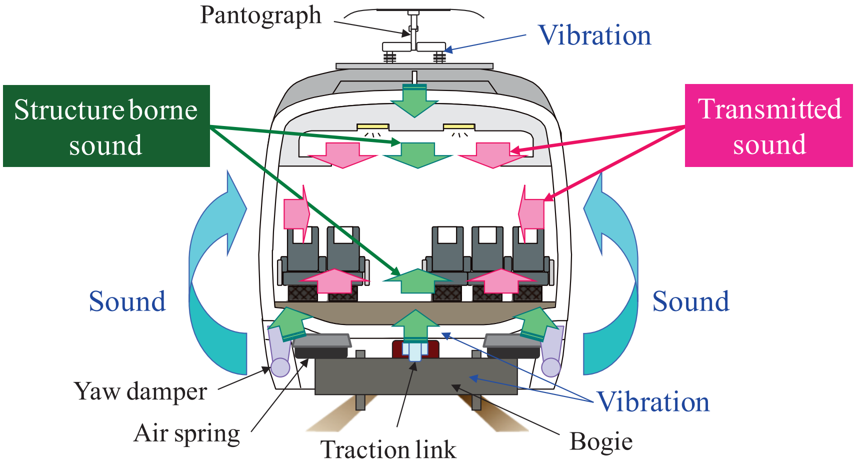


Figure 1 – Interior noise in railway vehicle

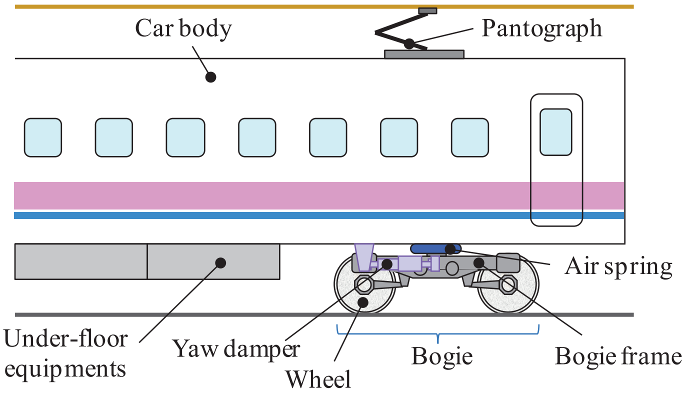


Figure 2 – Side view of a high-speed railway vehicle

2. TRANSFER PATH ANALYSIS CHARECTERISTICS

2.1 Operational Path Analysis (OPA)

Transfer path analysis (TPA) identifies the contribution of transfer paths from sound and vibration sources to a response point. TPA is regularly applied in the automobile industry to reveal the contribution ratios of each vibration transfer path. There are various methods in TPA. The matrix inversion method and the mount stiffness method are the main techniques used in traditional TPA methods. However, they have a number of drawbacks, including the considerable amount of effort and time required to derive the transfer functions and the insufficient precision of the identified input force [2]. Operational path analysis (OPA) is a new TPA technique that uses principal component analysis (PCA) [3]. Input points and an evaluation point (response point) are chosen in OPA to determine vibration acceleration and acoustic pressure at each part excited by various inputs. Subsequently, the transfer functions are derived between the input points and the evaluation point. Additionally, OPA generates synthetic vibration or sound at the evaluation point and calculates the contribution of every transfer path by multiplying the synthetic vibration or sound value with the transfer functions.

There are restrictions with respect to time and the experimental processes undertaken in the investigation of actual railway vehicles when compared to automobile analysis. Particularly, the identified input force is difficult to determine by traditional TPA methods. In OPA, restrictions exist in both cases in which the input data is independent or almost independent as well as in cases in which there are omitted transfer paths [4]. There is a possibility of obtaining measurements for a contribution analysis using the vibration accelerations of the bogie and car body and the acoustic pressures in the cabin while the vehicle is in motion. The achievement of such would be a great advantage.

As mentioned previously, there is a possibility that the relative independence of inputs could be a problem for railway vehicles, with respect to the traction links, yaw dampers, and air springs as input force points to the car body. In the low frequency region, the rigid motion of the bogie is considered dominant, and independence may only be assured in a sufficiently high frequency region. It is one of main scope of this paper to investigate this regard and to propose a process to confirm the validity to apply OPA from practical view.

2.2 Formulation of the Method

In OPA, the response at the evaluation point is considered as a superposition of vibration responses from n (n = 1, 2, …, N) input points. If the measurement is repeated m (m = 1, 2, …, M) times, the input/output relations are expressed as in Eqs. (1) and (2) using the transfer function vector $\{H(f)\}$ as follows:

$$\begin{Bmatrix} Y_1(f) \\ \vdots \\ Y_m(f) \\ \vdots \\ Y_M(f) \end{Bmatrix} = \begin{bmatrix} X_{11}(f) & \cdots & X_{1n}(f) & \cdots & X_{1N}(f) \\ \vdots & \ddots & & & \vdots \\ X_{m1}(f) & & X_{mn}(f) & & X_{mN}(f) \\ \vdots & & & \ddots & \vdots \\ X_{M1}(f) & \cdots & X_{Mn}(f) & \cdots & X_{MN}(f) \end{bmatrix} \begin{Bmatrix} H_1(f) \\ \vdots \\ H_n(f) \\ \vdots \\ H_N(f) \end{Bmatrix}, \tag{1}$$

$$\{Y(f)\} = [X(f)]\{H(f)\}, \tag{2}$$

where, $[X(f)]$ and $\{Y(f)\}$ denote the vibration response matrix of the input and the output, respectively.

It was desirable to adopt more than the number of inputs N for the number of measurement times M to adopt more than the number of inputs to derive the transfer function precisely. Therefore, $[X(f)]$ became a rectangular matrix with a lengthwise long primary line. The transfer function vector $\{H(f)\}$ was derived by multiplying the pseudo-inverse matrix $[X(f)]^+$ from the left, as shown in Eq. (3). Here $[*]^+$ indicates a pseudo-inverse matrix.

$$\{H(f)\} = [X(f)]^+\{Y(f)\}, \tag{3}$$

In OPA, principal component regression analysis is used when the noise is included in $[X(f)]$ and/or there is a high correlation among input signals [3]. When the input/output relation is shown using the derived transfer function, it is expressed as shown below (Eq. (4)):

$$Y(f) = \lfloor X(f) \rfloor \{H(f)\} = \sum_{i=1}^{N} H_i(f) X_i(f), \tag{4}$$

where $\lfloor * \rfloor$ denotes the line vector. Each item on the right side of Eq. (4) denotes the contribution of every transfer path. The input/output relation is expressed as a power spectrum density (PSD) as expressed in Eq. (5), by multiplying both sides of each equation by the complex conjugation shown in Eq. (4).

$$P_Y(f) = \sum_{n=1}^{N} |H(f)|^2 P_{Xn}(f), \tag{5}$$

where $P_{Xn}(f)$ is the PSD of input X_n (n = 1, 2, …, N), and $P_Y(f)$ is the PSD of output Y. Each item on the right side of Eq. (5) is the contribution of an input. In this study, these contributions are normalized such that the summation of the contributions at each frequency is equal to 1.

2.3 Investigation of Validity of Contribution

The validity of the transfer path contributions was investigated by checking the linearity of the input/output values and the independence of the input signals. When the correlation between the input data was high, it was conceivable that the estimated precision of the transfer functions derived with OPA falls. The checking the linearity of the input/output was to examine whether input with contribution was covered sufficiently to output, and is to evaluate the estimate accuracy of the transfer function derived by OPA.

The influence on correlation during data input was examined. The correlation during data input was estimated by calculating the correlation coefficient R. For the input data values x_1 and x_2, Eqs. (6)–(8) were used to calculate both the standard deviations σ_1 and σ_2 and the covariance C_{12}. Furthermore, based on the results, R was calculated by Eq. (9). In this regard, $\bar{x}_1$ and $\bar{x}_2$ denote the arithmetic averages.

$$\sigma_1 = \sqrt{\frac{1}{n}\sum_{i=1}^{n}\left(x_{1i} - \bar{x}_1\right)^2}, \tag{6}$$

$$\sigma_2 = \sqrt{\frac{1}{n}\sum_{i=1}^{n}\left(x_{2i} - \bar{x}_2\right)^2}, \tag{7}$$

$$C_{12} = \frac{1}{n}\sum_{i=1}^{n}\left(x_{1i} - \bar{x}_1\right)\left(x_{2i} - \bar{x}_2\right), \tag{8}$$

$$R = \frac{C_{12}}{\sigma_1\sigma_2}, \left(-1 \le R \le 1\right). \tag{9}$$

The correlation coefficient R indicated that there was a strong correlation near 1 or −1, which indicated a positive or negative correlation, respectively. At $R = 0$, there was no relation between the two data values.

Then, the multiple coherence function to examine the input/output relation was used to check the linearity of the input/output values. The multiple coherence function is represented by Eq. (10) as given below [5]:

$$\gamma_{multi}{}^2(f) = 1 - \frac{\det\{S_{YXX}(f)\}}{S_{YY}(f)\det\{S_{XX}(f)\}}, \tag{10}$$

where $S_{YY}(f)$ is the PSD of the output; $S_{XX}(f)$ is the matrix that has PSDs as the on-diagonal elements and cross-spectrum densities (CSD) between the inputs as non-diagonal elements; and $S_{YXX}(f)$ is the matrix, as expressed in Eq. (11):

$$S_{YXX}(f) = \begin{bmatrix} S_{YY}(f) & S_{Y1}(f) & \cdots & S_{Yn}(f) & \cdots & S_{YN}(f) \\ S_{1Y}(f) & S_{11}(f) & \cdots & S_{1n}(f) & \cdots & S_{1N}(f) \\ \vdots & \vdots & \ddots & \vdots & & \vdots \\ S_{nY}(f) & S_{n1}(f) & \cdots & S_{nn}(f) & \cdots & S_{nN}(f) \\ \vdots & \vdots & & \vdots & \ddots & \vdots \\ S_{NY}(f) & S_{N1}(f) & \cdots & S_{Nn}(f) & \cdots & S_{NN}(f) \end{bmatrix}, \tag{11}$$

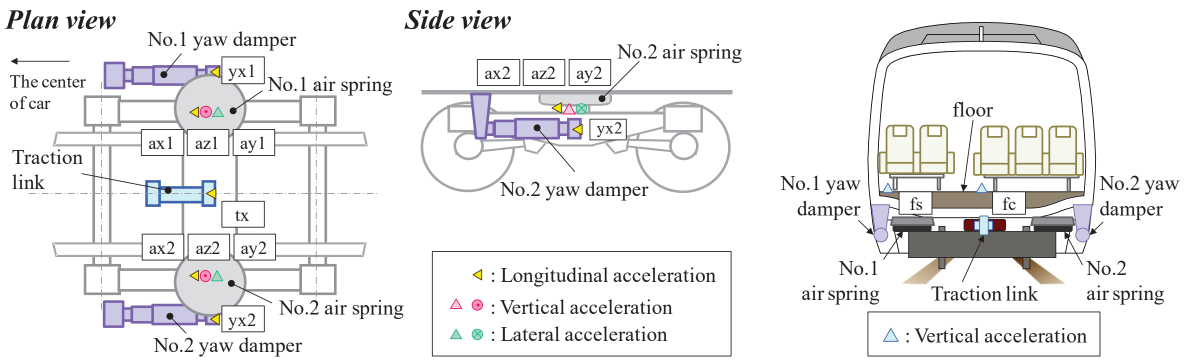
where $S_{Yn}(f)$ and $S_{nY}(f)$ are the CSDs between input n and output Y, $S_{nn}(f)$ is the PSD of input n, and $S_{nk}(f)$ is the CSD between input n and input k ($k = 1, 2, \ldots, N$). The value of the multiple coherence function estimated system linearity in linear systems with numerous inputs, and a value near 1 indicated high linearity.

3. APPLICATION TO THE STRUCTURE BORNE SOUND FROM THE BOGIE

3.1 Outline of High-Speed Train Running Tests

A series of running tests was conducted using high-speed train on a service line. In the running tests, the contribution ratios of each transfer path were evaluated by applying OPA using the measured data. The vibrations of the parts connecting the bogie and car body and of the cabin floor were measured. The contribution ratios of each transfer path were evaluated by applying OPA using the measured data. The measurement was carried out during running with constant speed on specified open sections (no tunnel sections) of 2 km – 6 km distance. 16 different cases of measurement data were obtained in the tests. The sampling frequency of the measurement was 3 kHz.

Figure 3 shows the measurement points for the running test. Figure 3 (a) shows the vibration acceleration measurement points on the parts connecting the bogie and car body. The acceleration pickups on traction link and yaw dampers were oriented in the longitudinal direction and those on the air springs were oriented in the three different directions. Measured acceleration data at total 9 points were used as input signals to the body (N = 9). Figure 3 (b) shows the vertical acceleration measurement points on the floor and the sound pressure measurement points in the cabin.



(a) On the parts connecting the bogie and the car body (b) On the floor

Figure 3 – Vibration acceleration measurement points at the running test

3.2 Contribution Ratio by Applying OPA to the Vibration Transfer Paths from the Bogie to the Floor

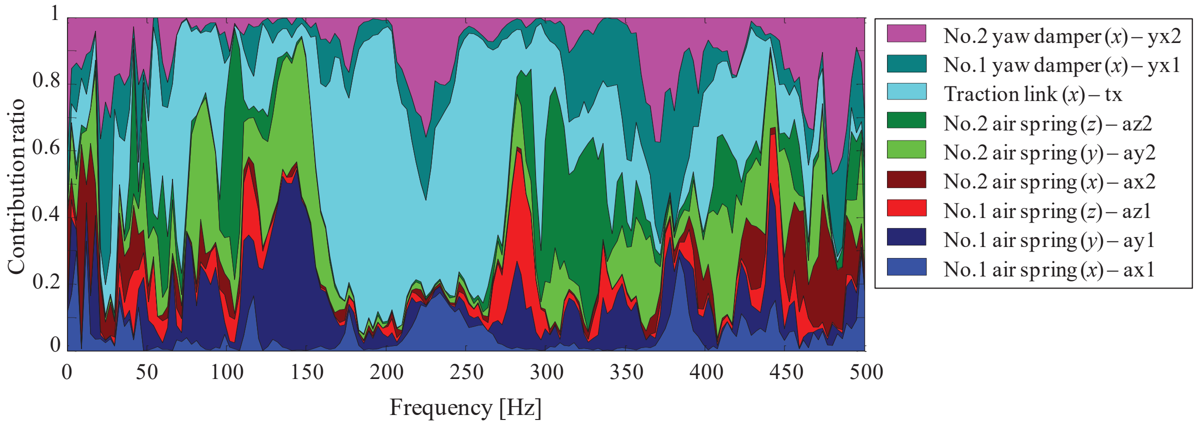
Figure 4 shows the contribution ratios at the center (point “fc” in Fig. 3 (b)) and side (point “fs” in Fig. 3 (b)) positions on the floor above the bogie. The contribution ratios were normalized so that the summation of the contribution ratios in each frequency was equal to 1. Figure 5 shows a comparison of the vibration acceleration PSDs of the actual measured values and the combined values at the evaluation points (fc and fs). Equation (5) was used to evaluate the combined values of the vibration acceleration PSDs at the evaluation points by using derived transfer functions. When considering all input/output relations, the values of the measured PSD of output and the combined PSD should be identical. If the values were not identical, it was considered to be affected by contribution from other transfer paths and noise.

At fc, the peak of the structure borne sound from the bogie at 100–300 Hz indicates a large contribution of Nos. 1 and 2 air springs between 100 and 150 Hz, and a significant contribution of the traction link around frequencies of 150–300 Hz as shown in Fig. 4 (a). The acceleration -measured PSD values and the combined PSD values were approximate at frequencies lower than 300 Hz as shown in Fig. 5 (a).

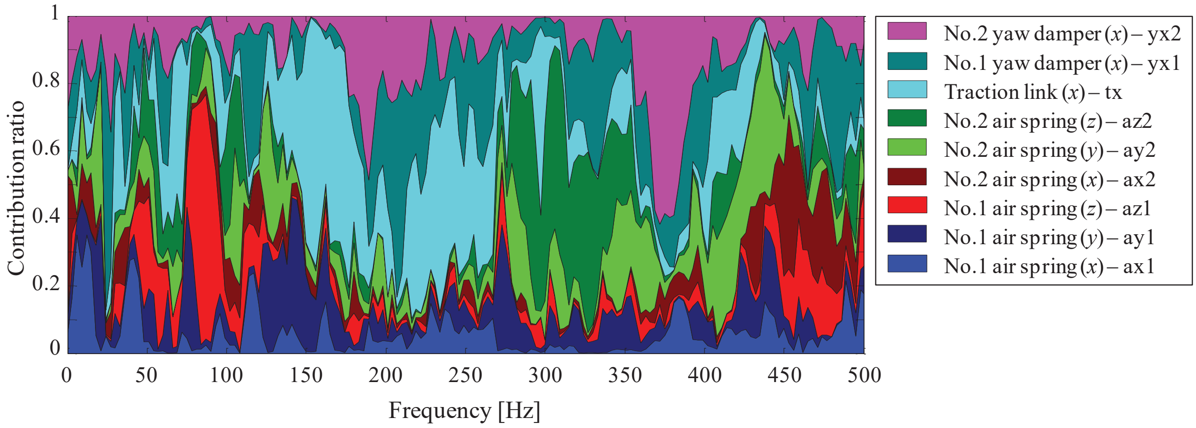
At fs, the contribution of No. 1 air spring was large between 100 and 150 Hz, and the contribution of the traction link and Nos. 1 and 2 yaw dampers were significant around frequencies of 200–250 Hz as shown in Fig. 4 (b). In particular, the contribution of No.1 yaw damper increased by 200–230 Hz. The combined PSD values diverged from the measured PSD values at frequencies exceeding 250 Hz as shown in Fig. 5.

3.3 Independence during Input Data

To apply OPA and to derive the highly precise transfer function, it is necessary that it is independent between the inputs or that correlation is low. Hence, the correlation coefficient of the vibration acceleration data between the parts connecting the bogie and car body was evaluated. An example of the result is indicated in Table 1. There was high independence with respect to each input since the coefficient of correlation was approximately less than 0.2. However, the correlation coefficients R of No. 1 air spring (ax1) and No.1 yaw damper (yx1) and of No. 2 air spring (ax2) and No. 2 yaw damper (yx2) were approximately 0.3. It could be regarded as a nearby between two combinations, as shown in Fig. 3 (a). Coherence functions were calculated for the two combinations, and the results are indicated in Fig. 6. These functions were determined for each point and revealed that multiple coherence functions were low at frequencies higher than 150 Hz, and that correlation was low. Furthermore, the coherences were also low at frequencies higher than approximately 100 Hz. Therefore, the correlations between the input data were low in the high frequency running tests, and it was possible to calculate the contribution ratios by applying OPA.

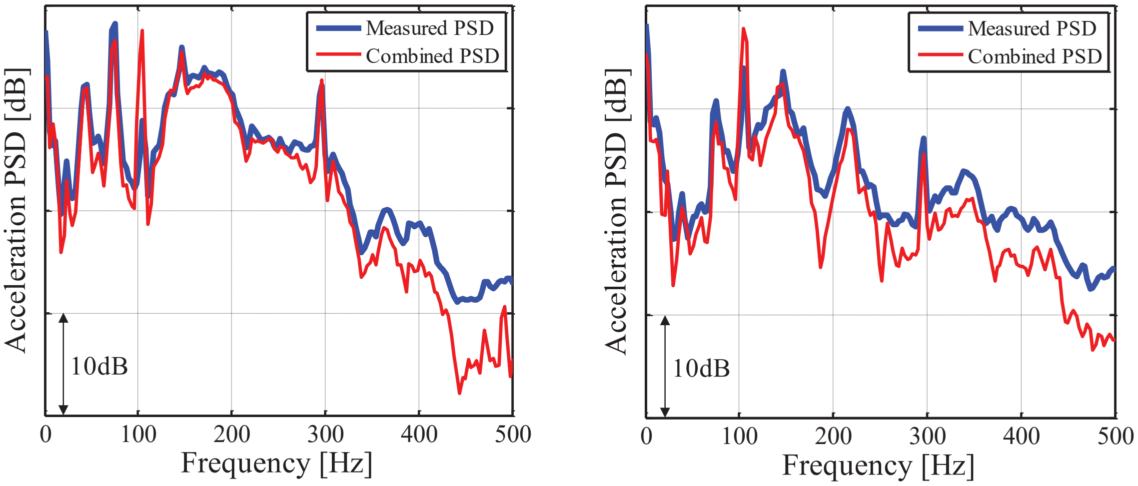


(a) fc



(b) fs

Figure 4 – Contribution ratios at the floor center (point "fc" in Fig. 3)
and at the side of the floor (point "fs" in Fig. 3) above the bogie.

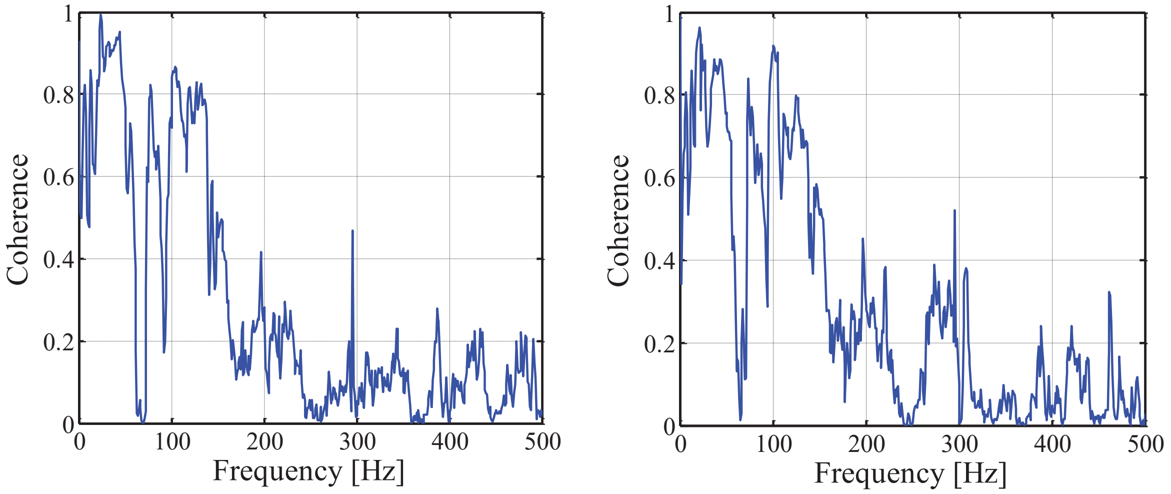


(a) fc (b) fs

Figure 5 – Comparison of the vibration acceleration PSDs of the actual measured values
and the combined values at the evaluation points ("fc" and "fs").

Table 1 – Correlation coefficients during data input (as an example)

Input points	Direction	Symbols	ax1	ay1	az1	ax2	ay2	az2	tx	yx1	yx2
No.1 air spring	Longitudinal	ax1	1.000								
	Lateral	ay1	-0.008	1.000							
	Vertical	az1	0.122	0.207	1.000						
No.2 air spring	Longitudinal	ax2	0.245	-0.144	0.002	1.000					
	Lateral	ay2	0.008	0.151	-0.039	0.077	1.000				
	Vertical	az2	0.073	0.063	0.174	-0.009	-0.283	1.000			
Traction link	Longitudinal	tx	0.045	-0.108	0.020	-0.103	0.081	0.078	1.000		
No.1 yaw damper	Longitudinal	yx1	-0.292	-0.002	-0.051	-0.106	-0.011	0.007	-0.065	1.000	
No.2 yaw damper	Longitudinal	yx2	-0.116	0.158	0.033	-0.340	-0.088	0.076	-0.013	0.068	1.000



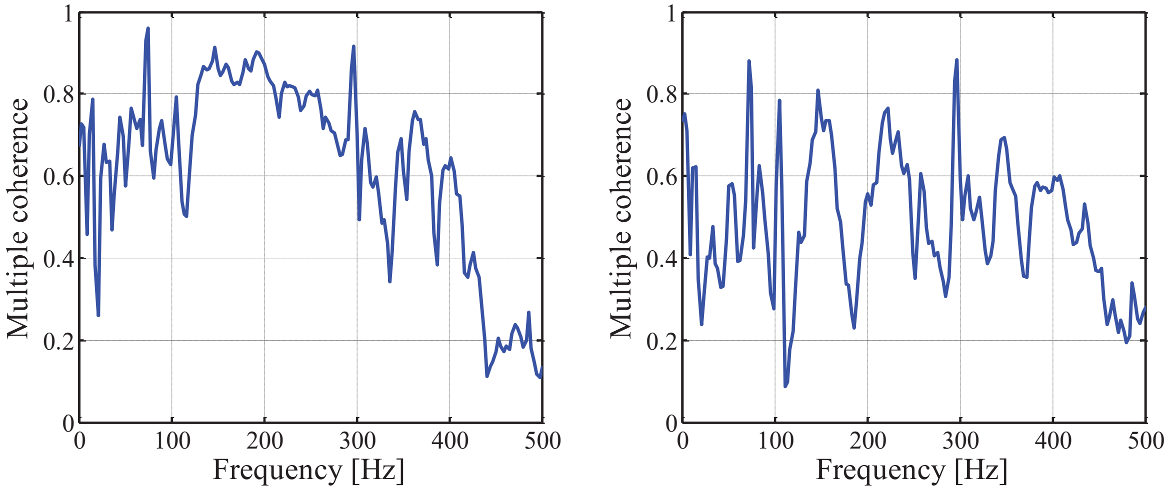
(a) ax1 and yx1

(b) ax2 and yx2

Figure 6 – Coherence functions

3.4 Validity of the Contribution Ratio Using the Multiple Coherence Function

Figure 7 shows the multiple coherence functions between the parts connecting the bogie and car body and the evaluation points. At fc, the values of the multiple relation function exceeded approximately 0.6 below 400 Hz. Hence, leakage was low in the selected input data, the derived transfer functions were highly precise, and the contribution was highly reliable, as shown in Fig. 7 (a). When fs is compared with the point fc, there are frequency bands with a low value of the multiple relation function, as shown in Fig. 7 (b). However, the value of the multiple relation function indicated high values of frequency at approximately 150 Hz and at the peaks of vibration acceleration PSD including frequencies of 150 and 200–250 Hz, as shown in Fig. 5 (b).



(a) fc

(b) fs

Figure 7 – Multiple coherence functions between the parts connecting the bogie and car body and the cabin floor evaluation points (“fc” and “fs”).

4. CONCLUSIONS

In this study, OPA was applied to the running test data of a high-speed vehicle and the transfer path contribution was calculated. The findings confirmed that OPA was effective in the structure borne sound from the bogie of railway vehicles. It was indicated that the confirmation procedure of the validity to apply OPA to structure borne sound from the bogies of railway vehicles. With the procedure, it revealed that it was possible to apply OPA in the frequency range of 100–300 Hz in case of the railway vehicle in this time. Additionally, the study revealed the following observations:

(1) The correlations during input data were low in the frequency range of 100–300 Hz. This was a peak of the structure borne sound from the bogie, and it was possible to apply OPA.

(2) At the floor center above the bogie, the contributions of Nos. 1 and 2 air springs were large between 100 and 150 Hz, and the contribution of the traction link was significant at approximate frequencies of 150–300 Hz.

(3) At the side of the floor above the bogie, the contribution of the nearby air spring was large between 100 and 150 Hz, and the contribution of the traction link and the yaw dampers were significant at approximate frequencies of 200–250 Hz. Particularly, the contribution of the nearby yaw damper was increased by 200–230 Hz.

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