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CONTRIBUTION ANALYSIS OF VEHICLE BODY VIBRATION MODE TO THE INTERIOR NOISE UTILIZING OPERATIONAL TPA

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In this study, we considered a method for selecting high contributing vehicle floor panel mode to the interior noise utilizing operational TPA (OTPA). A simple vehicle body model was employed and an operational test, in which swept sinusoidal forces were given from two points under the floor, was carried out. In the test, acceleration vibration at 15 points of the floor panel were measured as the reference signals and the interior noise was also measured as the response signal simultaneously for applying OTPA. Contributions of principal component (PC) were obtained by multiplying PC and the PC transfer function through the modified OTPA procedure. The frequency band, in which the floor vibration increased the interior noise mainly, was clarified by evaluating the PC and PC transfer function. In addition, high contributing body mode was extracted using the high contributing floor PC mode and the body vibration modes. Finally, the vehicle interior noise could be reduced well by applying intensive countermeasure to the high contributing vibration mode and the effectiveness of this method was clarified.

Keywords: operational TPA, vibration mode, principal component, vehicle interior noise

1. Introduction

Obtaining influence of each part to the vehicle interior noise quantitatively is important to reduce the noise efficiently. Transfer path analysis (TPA) is one of the methods for obtaining the contribution and several TPA methods have been proposed until now [1-9]. Operational TPA (OTPA) is a method calculating the contribution with smaller man-hour using only operational data [3,4,6,7,8,9]. The contribution is obtained by evaluating the relationship between multiple reference and response signals measured simultaneously [3]. The reference points is typically set around force input points (active part) such as engine mount attachment points and high contributing input part is obtained by this method [7]. In case the reference points are set at the body side (passive side), we can get to know which body part should be measured to reduce the vehicle interior noise [7]. However, when multiple reference points are set at close area or put on the same flame, many reference point vibrations becomes very similar. In such a case, contribution of each reference point also becomes very similar and we cannot find out high contributing part. Hence, we have developed a new operational TPA procedure for obtaining principal component (PC) contribution through modified OTPA calculation flow, and proposed a method to find out high contributing plate or frame vibration mode to the response point when single input was given [8,9]. However, it is considered that there are more input points to vehicle body in the actual condition in general. For increase the applicability of the new method and making the method more effective noise and vibration analytical tool, it is essential to verify whether the method can derive high contributing vibration mode or not in the multiple input situation. In addition, "principal component" (PC) that is calculated by extracting correlated component in reference signals and "principal component transfer function" (PC transfer function) that expresses relationship between the PC and response point were used for obtaining the PC contribution in the method. Then, if we can estimate which part or vibration mode increase the interior noise in each frequency band by using these information with the PC contribution, we can understand what we should do to reduce the vehicle interior noise more effectively using only the operational data.

In this study, we applied the new OTPA procedure employing PC model to a small vehicle body model having two input points. The interior noise and floor panel vibration were used as the response and reference signals. We attempted to find out at which frequency band the floor vibration increased the interior noise significantly by evaluating the PC and PC transfer function. Furthermore, we verified whether high contributing body vibration mode could be extracting or not by using the high contributing floor PC mode and body vibration modes in case multiple inputs were given At last, we tried to reduce the vehicle interior noise using the obtained high contributing vibration mode for the verification of the effectivity of the method.

2. Calculation procedure of OTPA

In the original OTPA, the contribution of each reference point to the response point is obtained by multiplying each reference signal with the transfer function. The transfer function in this method is calculated using a principal component regression method. The calculation procedure is shown in Fig. 1 [3].

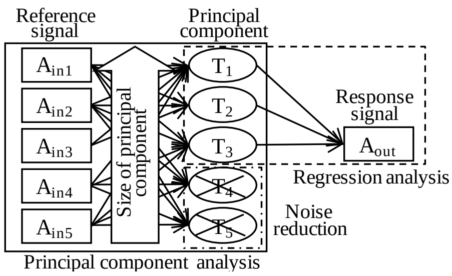


Figure 1: Calculation image of transfer function of OTPA using principal component regression.

The calculation procedure of contribution using operational TPA is described as follows.

1) Firstly, principal component analysis is applied to the reference signal matrix [A_{in}] by the singular value decomposition to remove correlation among reference signals as shown in Eqs. (1) and (2). The calculated uncorrelated signals are named as principal component [T]

$$[A_{in}] = [U][S][V]^T \tag{1}$$

$$[T] = [A_{in}][V] = [U][S] \tag{2}$$

2) Noise component in the uncorrelated signal is eliminated.
3) Multiple regression analysis is applied between the remained (signal) principal component [T] and the response signal [A_{out}] to obtain the influence [B] of each principal component to the response signal as shown in Eq. (3).

$$[B] = \left([T]^T [T]\right)^{-1} [T]^T [A_{out}] \tag{3}$$

4) Transfer function from reference signal to response signal [H] is calculated by multiplying the coefficient [V], that connects reference signal to principal component, and the regression coefficient [B], that connects principal component and response signal as shown in Eq. (4)

$$[H] = [V]\left([T]^T [T]\right)^{-1} [T]^T [A_{out}] \tag{4}$$

5) Finally, the reference point contribution and principal component contribution to the response point are calculated as shown in Eqs. (5) and (6), respectively

$$[A_{cont}] = [A_{in}][H] \tag{5}$$

$$[T_{cont}] = [T][B] \tag{6}$$

This is the outline for obtaining contributions by OTPA. Countermeasure of the response vibration is typically applied to the high contributing reference point. In this study, we utilized the principal component contribution as shown in Eq. (6) to choose high contributing vibration mode.

3. Operational test

3.1 Vehicle body model

In the operational test, a simple vehicle body model was used as shown in Fig. 2. Length, width and height were 550 x 300 x 300 mm. Total weight was 16.5 kg including four tires. Thickness of each body panel plate was from 1 to 4 mm and the material of the panel was Aluminium. The cavity surrounding by the panel was regarded as the vehicle interior in this test.

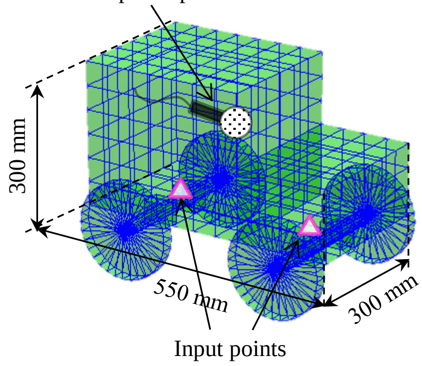


Figure 2: Vehicle body model.

3.2 Obtaining principal component contribution

Two input forces were given from under the floor plate as shown by two triangles in Fig. 2. Electrical magnetic exciters (Modalshop: K2007E01) were used to give the forces. Input signals were swept sinusoidal signals from 1 to 500 Hz for 30 s. The amplitudes of two input signals were different but the frequency of the sinusoidal signal was identical. The response signal (vehicle interior noise) was recorded using a microphone as shown in Fig. 2.

As the reference signal, measuring vibration at so many points around all the body panels require tremendous efforts. In case of the actual vehicle size, this sometimes makes unrealistic test situation. Hence, multiple points along vertical axis on the only floor panel (total 18 points) were used as the reference point signals as shown in Fig. 3. As a result, 19 signals including interior noise were measured simultaneously in this test.

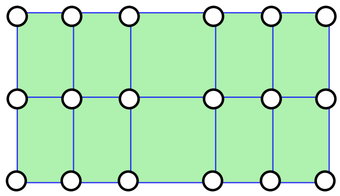


Figure 3: Floor panel vibration measurement points.

Figure 4 shows the averaged spectrum of the recorded vehicle interior noise at the test condition.

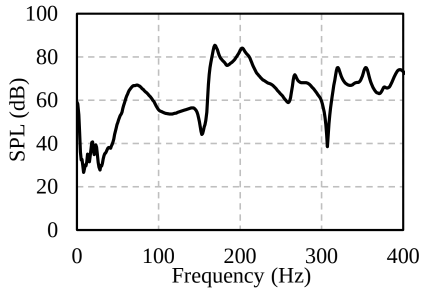


Figure 4: Sound pressure level of vehicle interior noise.

As shown in the figure, the sound pressure levels (SPLs) at 80, 170, 200 Hz were large and reduction of the interior noise at these frequency bands is necessary to reduce overall SPL. Then, the PC contribution was calculated using OTPA procedure with PC model using the measured multiple floor vibration (reference signals) and the interior noise (response signal). Figure 5 shows the calculated PC contribution from PC1 to PC4 averaged at the operational condition. Noting that 18 PC contributions are obtained theoretically according to the number of the reference point but only high contributing PC contributions from PC1 to PC4 were shown in the figure.

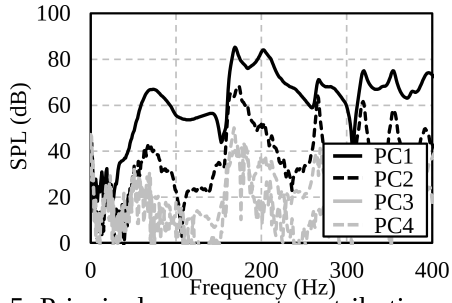


Figure 5: Principal component contribution of floor panel.

As shown in this figure, PC1 contribution was especially high, hence, further analysis was applied to the PC1 contribution.

3.3 Influence of floor panel vibration on the interior noise

PC1 contribution, which had largest contribution to the interior noise, PC1 level and PC1 transfer function were shown in Fig. 6 (a), (b), (c), respectively to understand which frequency band of the floor vibration had significant influence on the interior noise.

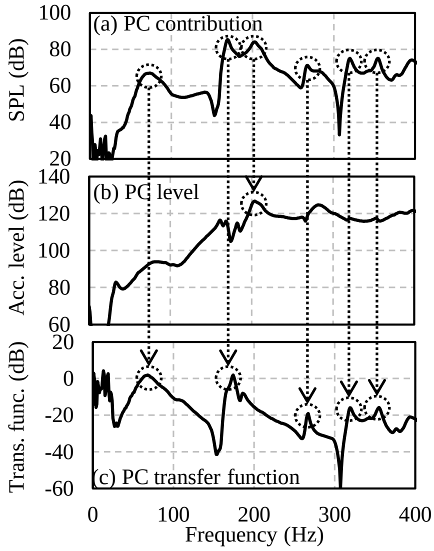


Figure 6: Contribution, level and transfer function of PC1.

As shown in Fig. 6 (a), PC1 contribution had several SPL peaks at the same frequency (80, 170, 200, 260, 320, 350 Hz) with the interior noise (Fig. 5) because PC1 had dominant contribution. Therefore, we can find out which makes the peak SPL by evaluating PC1 level and PC1 transfer function in each frequency band. The dotted circles in Fig. 6 (a) indicate PC1 contribution (interior noise) SPL peaks and the correspondent peaks in PC1 level and PC1 transfer function were indicated by the same dotted circles in Fig. 6 (b) and (c), respectively. As the result, the 200 Hz SPL peaks of the interior noise (Fig. 6 (a)) was found to be made by PC1 level (Fig. 6 (b)). This means floor panel vibration was large at the frequency and that made SPL peak in cabin. This also indicates the main factor of the interior noise at the frequency was the floor panel vibration.

On the other hand, the SPL peaks at 80, 170, 260, 320, 350 Hz in cabin was observed to correspond to PC1 transfer function. This reveals that the vibration of the floor did not make the SPL peaks in cabin at these frequencies but the other parts such as roof plate are considered to make them. In other words, applying countermeasure to the floor plate is not effective way to decrease the interior noise at these frequency bands.

From these analytical results, we could estimate which part (floor plate or the other parts) increases the interior noise in each frequency band by evaluating the frequency characteristics of PC1 contribution, PC1 level and PC1 transfer function. In the following section, we focused the vibration behaviour of PC1 having large influence of the interior noise at around 200 Hz and attempted to extract high contributing body vibration mode in many modes by associating the high contribution PC1 mode.

4. High contributing PC and vibration modes

High contributing PC mode and vibration mode were extracted after discussion of the theoretical background of PC mode and the relationship with the vibration mode.

4.1 PC mode

The PC matrix [T] obtained at the operational condition is calculated by the PC analysis which eliminates the correlation among reference signals as shown in Eqs. (1), (2). In addition, reference signals are also re-generated by multiplying PC matrix [T] with the inverse (transpose) matrix of unitary matrix [V] as shown in Eq. (6).

$$[A_{in}] = [T][V]^{-1} = [T][V]^{T} \tag{6}$$

The relationship between the reference signal and the PC can be developed as Eq.(7). Noting that the reference number is reduced to two for simple explanation.

$$\begin{bmatrix} a_{11} & a_{12} \\ a_{21} & a_{22} \\ \cdot & \cdot \\ a_{n1} & a_{n2} \end{bmatrix} = \begin{bmatrix} t_{11}v_{11} + t_{12}v_{12} & t_{11}v_{21} + t_{12}v_{22} \\ t_{21}v_{11} + t_{22}v_{12} & t_{21}v_{21} + t_{22}v_{22} \\ \cdot & \cdot \\ t_{n1}v_{11} + t_{n2}v_{12} & t_{n1}v_{21} + t_{n2}v_{22} \end{bmatrix} \tag{7}$$

In Eq. (7), the left solid box in the right matrix is the PC1 element in the reference signal 1 and the right solid box is the element in the reference 2. Left and right dotted boxes indicate the PC2 element in the reference signal 1 and 2, respectively. This means that the reference signal can be expressed by the superposition of the PC elements. In addition, each PC has orthogonality (no-correlation) with the other PC theoretically by the PC analysis. The PC element has complex value (amplitude and phase), hence, PC vibration behaviour (PC mode) can be obtained. From these background, PC mode has been regarded as the vibration mode excited at the operational condition [8,9].

4.2 High contributing PC mode

We focused on the PC1 mode at around 200 Hz, which made SPL peak in cabin. The PC1 mode was calculated using amplitude and phase information of each PC element in each reference signal as shown in Eq. (7). Figure 7 shows the PC1 mode at 205 Hz, where the PC1 of the floor vibration had peak.

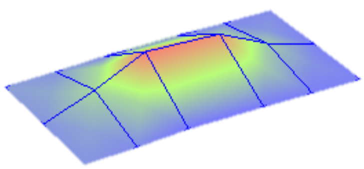


Figure 7: PC1 mode of floor panel at 205 Hz.

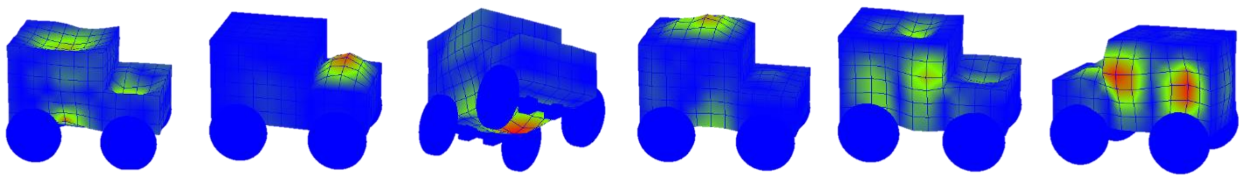
As shown in the PC1 mode shape, the floor panel vibration was found to be large at the center of the floor panel and applying a countermeasure to constrain the center part seems to be effective to reduce interior noise at the frequency band. On the other hand, the PC mode was expressed using the measured reference signals and the number of the reference point is occasionally not enough to express the vibration behaviour in detail according to the mode shape. In addition, the PC mode does not associate with the vibration mode at present, hence, it is hard to consider the structure or material modification for reduction of the vibration. Then, we attempted to extract high contributing body vibration mode in a lot of modes by associating the high contributing PC1 mode in the following section.

4.3 Vibration mode of the vehicle body model

Vibration modes of the employed vehicle body model were obtained by experimental mode analysis. In the impact measurement test, input force was given at the center of the floor panel by the same exciter in the operational test and the response point was moved on the all body plates to obtain multiple transfer functions. The response points were set at mesh crossing point (total 424 points) as shown in Fig. 2. Obtained natural frequencies and damping ratios less than 400 Hz are shown in Table 2. The representative mode shapes of the body are shown in Fig. 8 (a) to (f).

Table 1: Vibration modes of vehicle body model.

	Mode01	Mode02	Mode03	Mode04	Mode05	Mode06	Mode07	Mode08	Mode09	Mode10	Mode11	Mode12	Mode13	Mode14
Freq. (Hz)	26.5	33.2	79.5	97.8	142	164	181	216	261	294	332	355	373	396
Damp. (%)	1.92	2.09	3.82	3.72	7.49	3.56	2.45	3.13	7.4	2.96	7.14	3.95	4.04	4.8



(a) Mode 03 (79.5 Hz) (b) Mode 06 (164 Hz) (c) Mode 08 (216 Hz) (d) Mode 09 (261 Hz) (e) Mode 11 (332 Hz) (f) Mode 12 (355 Hz)

Figure 8: Representative vibration mode shapes of the whole body.

As shown in Fig. 8 (c), the vibration mode shape of Mode 08 at 216 Hz had antinode at the center of the floor plate. The frequency was similar with that where PC1 mode of the floor plate was the main factor of SPL peak in cabin. Therefore, the generated large vibration of the floor plate is considered to increase the sound pressure in cabin and make the SPL peak at the frequency band. In addition, the vibration mode shapes of Mode 03, Mode 06, Mode 09, Mode 11, Mode 12 were observed to have large antinode at the different part from the floor plate such as side plate and bonnet as shown in Fig. 8 (a), (b), (d), (e), (f), respectively at 80, 164, 261, 332, 355 Hz, where PC transfer function was the main factor of the SPL peaks in cabin at the approximately same frequency bands. According to these body vibration mode shapes, it was clarified that PC level of the floor plate vibration did not give significant influence on the SPL peaks but PC transfer function had similar peaks with the SPL in cabin. From these results, the obtained information about the main factor of the SPL peaks in cabin using only PC and PC transfer function through OTPA employing PC model was verified to indicate the correct tendency.

4.4 High contributing body vibration mode

From the previous analyses, PC1 mode of the floor plate at around 200 Hz was found to be a main factor of the large SPL peak in cabin. In addition, the vehicle body model had vibration mode at 216 Hz, in which floor plate moves largely. However, the frequency between the PC1 mode and the vibration mode was not the same. Then, we evaluated the similarity of the relative amplitude and phase in the reference points between the PC1 mode and the vibration mode for obtaining high contributing vibration mode associating with the high contributing PC1. The mode shape correlation was calculated between the high contributing PC1 mode at 205 Hz and each vibration mode. Table 2 shows the calculated mode shape correlation of the body vibration modes with the high contributing PC1 mode. In the calculation of the mode shape correlation, the data of the vibration mode only at the same position with the reference point in the operational test was used.

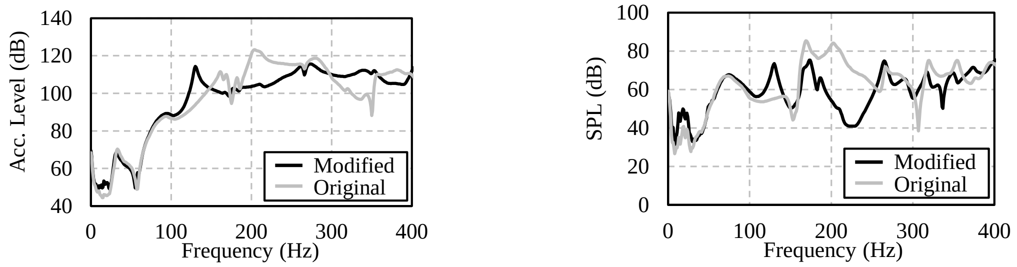
Table 2: Vibration mode shape correlation to high contributing PC mode.

	Mode01	Mode02	Mode03	Mode04	Mode05	Mode06	Mode07	Mode08	Mode09	Mode10	Mode11	Mode12	Mode13	Mode14
Freq. (Hz)	26.5	33.2	79.5	97.8	142	164	181	216	261	294	332	355	373	396
Mode cor.	0.04	0.07	0.35	0.36	0.14	0.14	0.68	**0.97**	0.10	0.23	0.04	0.18	0.43	0.05

As shown in the table, high contributing PC1 mode at 205 Hz was observed to have very high correlation with Mode 08 at 0.97. This reveals that the Mode 08 was the high contributing vibration body mode associating with the PC1 mode at around 200 Hz. And the reduction of this vibration mode is considered to be essential for the reduction of the vehicle interior noise at the frequency.

5. Noise reduction considering high contributing vibration mode

In this section, we attempted the vehicle interior noise reduction at 200 Hz band where the floor plate vibration gave large influence to the noise. For the noise reduction, we focused on the high contributing vibration mode of Mode 08 associating with the high contributing PC1 mode. To constrain the large vibration amplitude at the center of the floor plate, 500 g concentrate weight was put at the center of the floor plate. After then, the vehicle interior noise and the floor vibration were again measured in the same operational condition. Figure 9 (a) and (b) shows the comparison before and after the countermeasure in the floor vibration at the center point and the interior noise.



(a) Vibration comparison at the center of the floor panel. (b) Vehicle interior noise comparison.

Figure 9: Vibration and vehicle interior noise before and after countermeasure.

As shown in Fig. 9 (a), the floor vibration could be reduced well at around 200 Hz by putting the weight, where the vibration was estimated to have significant influence on the vehicle interior noise. As same as the floor vibration reduction, the SPL of interior noise was reduced very well at around the same frequency according to the floor vibration reduction as shown in Fig. 9 (b). This shows that the floor vibration had actually high contribution to the vehicle interior noise at the frequency band as indicated by the OTPA employing PC model.

6. Summary

In this study, we attempted to obtain high contributing vibration mode to the vehicle interior noise by applying OTPA employing PC model. We also considered how to estimate the main factor of the SPL peaks of interior noise using PC and PC transfer function consisting PC contribution.

As a result, it was clarified that when the PC level of the floor vibration is large at a frequency band, the floor vibration is the main factor of the SPL peak in cabin and floor plate should be measured intensively for the reduction of the interior noise as verified in the actual countermeasure. On the other hand, when the PC transfer function made the SPL peaks in cabin, the other parts are considered to be the main factor, hence, we had better applying the countermeasure to the other part from the floor plate. In addition, the method was found to be able to find out high contributing vibration mode to the interior noise by associating high contributing PC mode with them in case multiple inputs were given to the structure. This shows the proposed method utilizing PC model has a potential to be applied in the actual vehicle to find out in which frequency the focused plate gives significant influence of the interior noise and important vibration mode. Furthermore, this method can be applied to the simulated vibration mode by CAE technique. Through the combined analyses of the OTPA with PC model and CAE, we can find out high contributing vibration mode to the interior noise in many simulated modes.

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