Analytical method for vehicle interior noise using principal component contribution
-Contribution analysis of whole body vibration behavior through separated measurement-

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ABSTRACT

In this study, we developed a method to obtain important whole body vibration behavior and the contribution to the vehicle interior noise by using principal component (PC) contribution analysis. This method originally requires all reference and response signals to be measured simultaneously. However, if the target structure is large and a number of signals are necessary to be measured, applying this method becomes difficult depending on the measurement system. The proposed method in this study was made to increase the applicability by obtaining the whole body vibration behavior and the contribution without the simultaneous measurement. In the method, several operational tests were repeated to each measurement group. The vibration behavior (partial PC mode) and the contribution were then obtained. Subsequently, high contributing whole body PC mode and the contribution to the response point was estimated by integrating the partial PC modes and the contributions. Through the procedure, the high contributing whole body PC mode and the contribution could be obtained well with less measurement points.

Keywords: Transfer path analysis, Principal component, Vibration mode
I-INCE Classification of Subject Number: 74, 75

1. INTRODUCTION

For carrying out effective countermeasure to vehicle interior noise, finding out main contributors from sound or vibration sources and measuring the part intensively is essential. Transfer path analysis (TPA) was proposed to obtain the contribution quantitatively[1-6]. Operational TPA (OTPA) is one methods recently developed and the method calculates the contribution using only the sound and vibration signals under the operational condition[2,4-6]. Recently, modified OTPA method (OTPA with principal component model) has also been proposed as the principal component (PC) contribution analysis for calculating contribution of the PC vibration to the vehicle interior noise or vibration to obtain the important vibration behavior of the target structure[7,8].

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However, if we apply this method to a large structure such as a vehicle body to obtain the vibration behavior in detail, a lot of reference points have to be measured at around the body on the contrary to the original OTPA. This requires the huge number of simultaneously measurements of the reference and response point signals. Hence, if we do not have adequate numbers of acceleration sensors and measurement system, this method cannot be applied. On the other hand, mode analysis is one methods for obtaining vibration mode and the natural frequency of the large structure with small experimental set up. However, all vibration modes of the structure are not excited in general by the frequency characteristic of the input force and the input point. Therefore, finding out which vibration mode affects largely to the interior noise is important to carry out effective countermeasure.

In this study, we then considered a separating measurement and analytical methods for the PC contribution analysis to obtain the integrated contribution of the whole body PC vibration and the behavior of the whole body having large influence on the interior noise to increase the applicability of the method.

2. CALCULATION OF PC CONTRIBUTION[7,8]

2.1 Reference and PC contribution calculation

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 PC regression method as follows.

PC analysis is firstly applied to the reference signal matrix $[A_{\mathrm{in}}]$ by singular value decomposition (SVD) to remove correlation among reference signals as shown in Eqs. (1) and (2). The calculated uncorrelated signals are PC $[T]$.

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

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

The reference signal matrix $[A_{\mathrm{in}}]$ is obtained by applying FFT repeatedly to the simultaneously measured vibration signals at the reference points. The (i, j)-th element in the reference matrix $[A_{\mathrm{in}}]$ is the data at the j-th reference point in the i-th FFT. Matrices $[U]$, $[S]$, and $[V]$ are obtained as the result of SVD. Here, $[V]$ is the coefficient matrix to transpose the reference matrix $[A_{\mathrm{in}}]$ to the PC matrix $[T]$. The (i,k)-th element in $[T]$ is the k-th PC in the i-th FFT. After eliminating the noise component having very low level, multiple regression analysis is applied between the remained (signal) PCs $[T]$ and the response signal $[A_{\mathrm{out}}]$ to obtain the influence $[B]$ of each PC to the response signal as shown in Eqs. (3) and (4).

$$[A_{out}] = [T][B] \tag{3}$$

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

The (i,m)-th element in the response matrix $[A_{\mathrm{out}}]$ is the data at the m-th response point in the i-th FFT. The (k, m)-th element in the transfer matrix $[B]$ is the transpose coefficient from the k-th PC to the m-th response point. Transfer function from reference signal to response signal $[H]$ is calculated by multiplying the coefficient $[V]$, that connects reference signal to PC, and the regression coefficient $[B]$, that connects PC and response signal as shown in Eq. (5)

$$[H]=[V]\left([T]^T[T]\right)^{-1}[T]^T[A_{out}] \tag{5}$$

The (j, m)-th element in the transfer matrix [H] is the transfer function from the j-th reference point to the m-th response point. Finally, the reference point contribution and PC contribution to the response point are calculated as shown in Eqs. (6) and (7), respectively.

$$[A_{cont}]=[A_{in}][H] \tag{6}$$

$$[T_{cont}]=[T][B] \tag{7}$$

Equations (6) and (7) show the contribution of reference point and the contribution of the PC, respectively. Here, the PC contribution [T_{cont}] is obtained by multiplying the calculated PC signal [T] in Eq. (2) with the transpose coefficient [B] in Eq. (4). This is the outline for obtaining contributions by OTPA. In this study, we focused on the PC contribution as shown in Eq. (7) to obtain important vibration behavior for the reduction of the response signal[7,8].

2.2 High Contributing PC Mode[7,8]

The PC matrix [T] is calculated by the PC analysis which eliminates the correlation among reference signals as shown in Eqs. (1) and (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. (8).

$$[A_{in}]=[T][V]^{-1}=[T][V]^T \tag{8}$$

Here, the relationship between the reference signals and the PCs can be developed as follows (Eq. (9)). Noting that the reference number is reduced to two for simple explanation.

$$\begin{bmatrix} a_{11} & a_{12} \\ a_{21} & a_{22} \\ \cdot & \cdot \\ a_{n1} & a_{n2} \end{bmatrix} = \begin{bmatrix} \boxed{t_{11}v_{11}} + t_{12}v_{12} & \boxed{t_{11}v_{21}} + t_{12}v_{22} \\ t_{21}v_{11} + t_{22}v_{12} & t_{21}v_{21} + t_{22}v_{22} \\ \cdot & \cdot \\ t_{n1}v_{11} + t_{n2}v_{12} & t_{n1}v_{21} + t_{n2}v_{22} \end{bmatrix} \tag{9}$$

In Eq. (9), the left solid box in the right part is the PC1 element in the reference signal 1 and the right solid box is the element in the reference signal 2. Left and right dotted boxes indicate the PC2 elements in the reference signal 1 and 2, respectively. This means that the reference signal can be expressed by the superposition of PC element. In addition, each PC has orthogonality (no correlation) with the other PC by the PC analysis. From these background, PC mode is considered to have similar characteristics of the vibration mode excited at the operational condition and several previous studies focused the high contributing PC mode for extracting high contributing vibration mode to the vehicle interior noise[7,8]. However, all reference point acceleration signals have to be measured simultaneously with the response point signal to obtain the PC contribution and the high contributing PC mode in this method. Hence, when we apply the method to the large structure such as the vehicle body, a few hundreds of sensors and measurement systems are necessary and this may increase the difficulty to apply this method. Then, we considered a new method for increasing the applicability of the PC contribution analysis by separating the measurement and integrating the analytical results to obtain the contribution of the whole vehicle body and the high contributing PC mode to the vehicle interior noise.

3. OPERATIONAL TEST IN SEPARATED MEASUREMENT[9]

3.1 Employed vehicle model

Simple vehicle body model was made for the operational test as shown in Fig. 1. The length, width and height were 850 x 300 x 300 mm. Total weight was 25 kg including four tires. Thickness of each body panel was 3 mm and the material of the panel was Aluminium. The cavity surrounding by the panel was regarded as the vehicle interior.

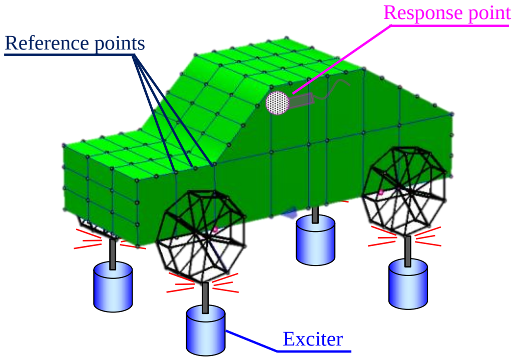


Fig. 1 Vehicle body model made for the operational test.

As the input force, four electrical magnetic exciters (Modalshop: K2007E01) were put under the four tires and uncorrelated random noise was given to each tire for 50 s. As the response point signal, vehicle interior noise was recorded by a microphone in cabin as shown in Fig. 1. As the reference point, a lot of measurement points had better to be set for obtaining detail vibration behavior of whole body. However, this method requires simultaneously measurement of all reference and response signals, hence, the analysis may be unrealistic if the target structure is large. Then, we attempted to apply this method through separated measurement. Accordingly, the reference points around the body were separated in each panel and the reference point number varied from 16 to 24 in each panel. Thus, the operational test was carried out in total nine times. In each test, the reference point signals of a panel and the identical response signal (interior noise) was recorded simultaneously in the same input condition. Figure 2 shows the averaged SPL of interior noise when the reference points were set on the left side panel where 22 reference points were set as an instance.

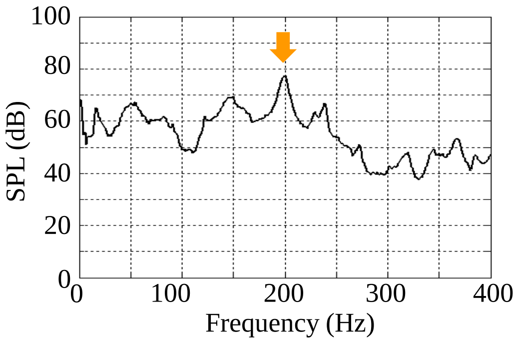


Fig. 2 Sound pressure level of interior noise under the operational test.

As shown in the figure, the interior noise was found to have large SPL peak at around 200 Hz. Then, this frequency was set as the target frequency for the following analysis to obtain the contribution of the whole body PC and the PC mode.

3.2 Obtaining partial PC contribution (Left side panel)

As the first analysis, we applied PC contribution analysis to the simultaneously measured vibration acceleration signals (reference signals) on the left side panel and the interior noise (response signal). Figure 3 shows the averaged "partial" PC contributions of PC1 to PC4 having relatively larger influence to the response point in total 22 PCs.

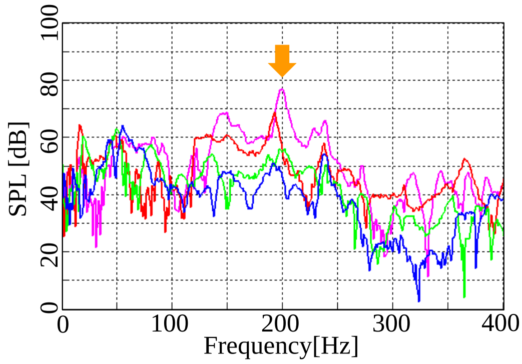


Fig. 3 Calculated partial PC contribution of left side panel.

As shown in the result, PC1 of the left side panel was observed to be dominant contribution at around 200 Hz band. Then, the PC1 mode of the target panel was obtained in the following analysis.

3.3 High contributing partial PC mode (Left side panel)

We calculated the high contributing PC1 mode at 200 Hz, where large SPL peak was found at interior, when the target panel was set on the left side. Figure 4 shows the PC1 mode calculated by using Eq. (9) at 200 Hz.

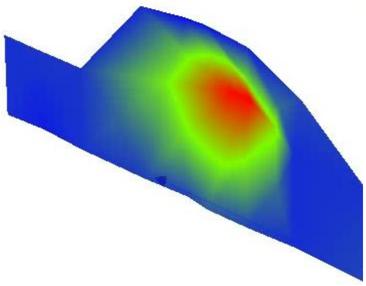


Fig. 4 High contributing PC1 mode of left side panel at 200 Hz.

As shown in this figure, the PC mode was found to have large vibration at the center of the left side panel. However, this PC mode only shows the vibration behavior of the left side panel and considering suitable countermeasure to the whole body using only this information is hard. Furthermore, the PC1 contribution may not be the important (dominant) PC of the whole body vibration to the interior noise according to the influence of the other panels. Then, we considered a method to obtain the whole body PC contribution and the vibration behavior affecting largely to the vehicle interior noise through the separated measurement.

4. INTEGRATED HIGH CONTRIBUTING PC CONTRIBUTION AND PC MODE OF WHOLE BODY

4.1 Methodology[9]

Operational test was repeated in this study by setting reference points on each panel, and the partial PC contribution was obtained. Here, we attempted to obtain the PC contribution of the "whole" body and the PC mode by using the "partial" PC information of each panel. Then, we considered an integrating method to obtain the whole body PC contribution and the mode affecting largely to the interior noise. In this method, we firstly calculated the high contributing PC mode of the whole body by compensating the amplitude and phase relationship using the response point information and then, the PC contribution and the PC transfer function of the whole body to the interior noise was estimated as follows.

In case a PC mode of panel A (PC_A mode) is a part of the global (whole body) vibration mode, the time variance of PC_A amplitude under the operational condition has perfect correlation with the time variance of the amplitude of the global vibration mode. In addition, if the global vibration mode has large influence on the interior noise (reference signal) and the correlation of them is 0.8, the PC_A mode must have the same correlation (0.8) with the response signal in the operational test as shown in Fig. 5. On the other hand, in case a PC mode of panel B (PC_B mode) is also a part of the same global vibration mode, the time variance of PC_B in the other operational condition has perfect correlation with the global vibration mode. And the PC_B mode also has the same correlation (0.8) with the response signal in the operational test as same as PC_A. This means if both PC_A and PC_B modes are part of the identical global vibration mode having large influence on the response signal, the correlation of each partial PC mode to the response signal in each separated operational test becomes similar and high. Then, we supposed that the associated high contributing partial PC mode for all panels can be found by using the correlation between each partial PC and the response signal in each operational test.

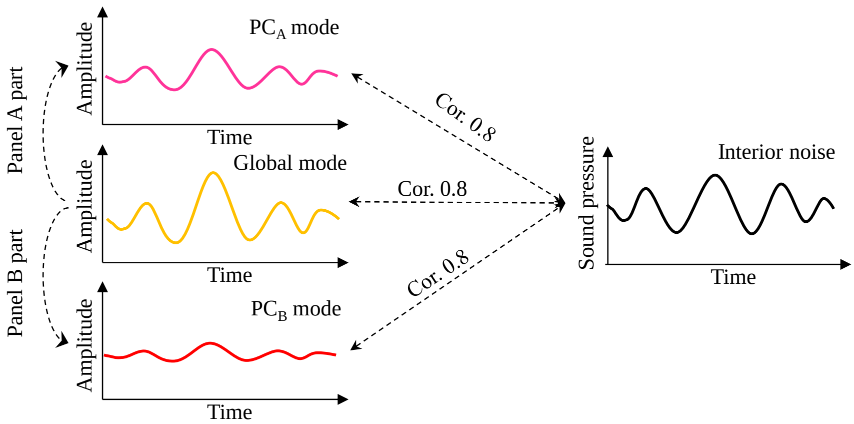


Fig. 5 Image of related PC of each panel and the response point[9].

After obtaining the associated high contributing partial PC number in each panel, we subsequently compensated the phase and amplitude relationship of the partial PC mode in each panel for obtaining the integrated high contributing whole body PC mode. To obtain relationship of each partial PC mode, the amplitude and phase of high contributing partial PC is calculated if unit response signal (interior noise) is observed by the PC by using the PC transfer function ([B]) in Eq. (7) as shown in Fig. 6. Subsequently, the amplitude and phase of the reference points composing the partial PC in the target panel are also calculated by using the transpose coefficient matrix [V] in

Eq. (2). By applying this process to each partial PC mode in each panel, the phase and amplitude compensated partial PC mode is obtained.

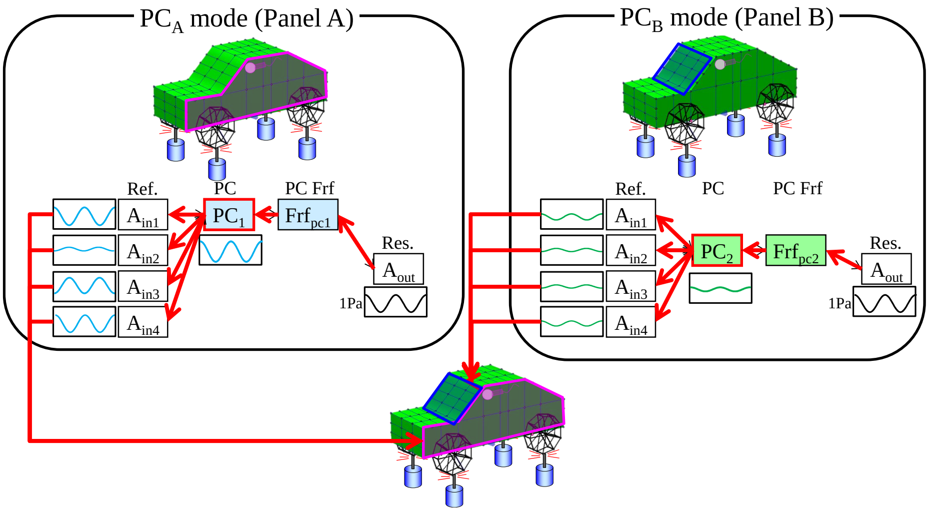


Fig. 6 Image of compensation of relative amplitude and phase.

4.2 Obtaining integrated high contributing PC mode of the whole body

In this part, we obtained the high contributing whole body PC mode at the target frequency (200 Hz). The correlation coefficient of each PC and the response signal were calculated in each operational test to find out the associated PC number of each panel. Figure 7 shows the coefficient from PC1 to PC4 having relatively large level in all PCs.

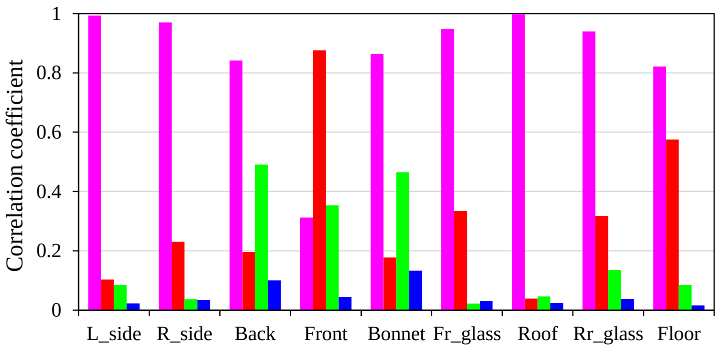


Fig. 7 Correlation coefficient of each PC and the response signal.

As shown in this figure, PC1 had largest correlation with the response signal in most panels except for front panel. This indicates that PC1 in most panels and PC2 in the front panel were high contributing partial PC modes and they composed the high contributing whole body PC mode. Secondly, the whole body high contributing PC mode at 200 Hz was made after calculating compensated phase and amplitude of each reference point of each high contributing partial PC mode by using the unit response signal. Figure 8 shows the integrated high contributing whole body PC mode.

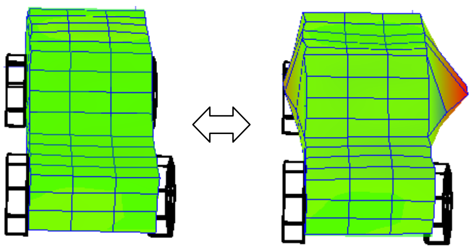


Fig. 8 Integrated high contributing whole body PC mode at 200 Hz.

As shown in the figure, the high contributing whole body PC mode was found to have large vibration on the center of left and right side panels. The amplitude of the left side panel was larger than the right side panel and the phase of them was opposite. Subsequently, the vibration mode of the target structure at around 200 Hz was obtained through the experimental mode analysis to verify whether the integrated whole body PC mode actually indicates the global vibration mode and the effectiveness of using PC mode. As the result, two vibration modes were observed at 192 and 201 Hz as shown in Fig. 9. Figure 9 shows the point inertance at the center of the left side panel and the vibration mode shapes. Through the comparison of the integrated whole body PC mode in Fig. 8 and the vibration modes at around 200 Hz in Fig. 9, the high contributing PC mode (Fig. 8) at 200 Hz was observed to have very similar vibration behavior with the vibration mode at 201 Hz but the mode shape was quite different from the vibration mode at 192 Hz. This shows that this method could extract the high contributing vibration mode in a few modes by using the integrated high contributing PC mode.

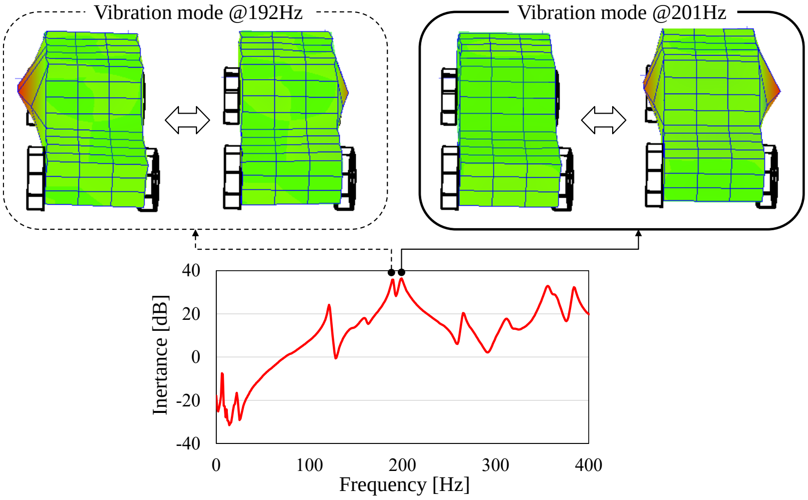


Fig. 9 Point inertance at the center of the left side panel and the vibration mode shapes at 192 Hz and 201 Hz obtained by the experimental mode analysis.

4.3 Calculating contribution of the integrated PC and the transfer function of the whole body

In the OTPA with PC model, the contribution (interior noise) is obtained by multiplying the PC level and the PC transfer function as shown in Fig. 10. Figure 10 is the image of relationship of PC contribution, PC level and PC transfer function.

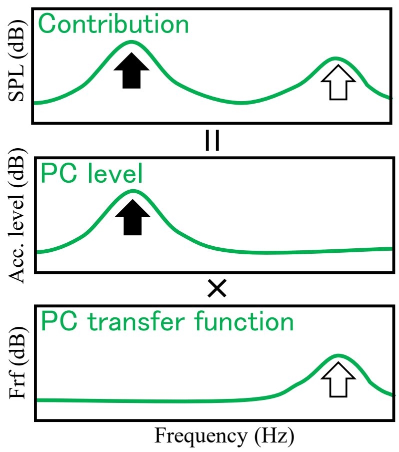


Fig. 10 Image of relationship among PC contribution, PC level and PC transfer function.

If the response signal is large at a frequency band as indicated by filled arrow in Fig. 10 where the PC level also has a peak, the countermeasure had better to be applied at the target structure because the peak was made by the vibration characteristic of the structure. On the other hand, in case the PC transfer function generates the response signal peak as indicated by opened arrow, the other part of the structure such as the resonance in cabin is supposed to make the peak. Accordingly, if we can determine which part (PC level or PC transfer function) makes the interior noise peak, more effective countermeasure can be applied. Then, we considered the method for evaluating the factor of the interior noise peak at the operational condition. For the method, the whole body PC level and the PC transfer function was estimated by utilizing an operational data set in a separated measurements as the master data. The calculation steps are described as follows;

1. Partial PC contribution (partial PC level and the transfer function to the response signal) is calculated in each panel by the original PC contribution analysis.
2. PC number having the highest correlation to the response signal is obtained in each panel (Obtaining associated PC number among panels).
3. Contribution of the high contributing partial PC in the master data set (e.g., left side panel) is stored in each frequency (Preparation of master response signal as shown in left side of Fig. 11).
4. High contributing partial PC amplitude of each panel is estimated by dividing the master response signal by the PC transfer function as shown in right side of Fig. 11 (The amplitude and phase relationship among panels were compensated through this procedure).
5. Reference signals of each panel including only the high contributing partial PC element is re-generated using the relationship between each partial PC and the reference signal as shown in right side of Fig. 11 ([*B*] matrix in Eq. (3)).
6. PC contribution analysis is again carried out to the calculated all reference point signals for obtaining the whole body PC level and the PC transfer function to the master response signal in each frequency as shown in Fig. 12.

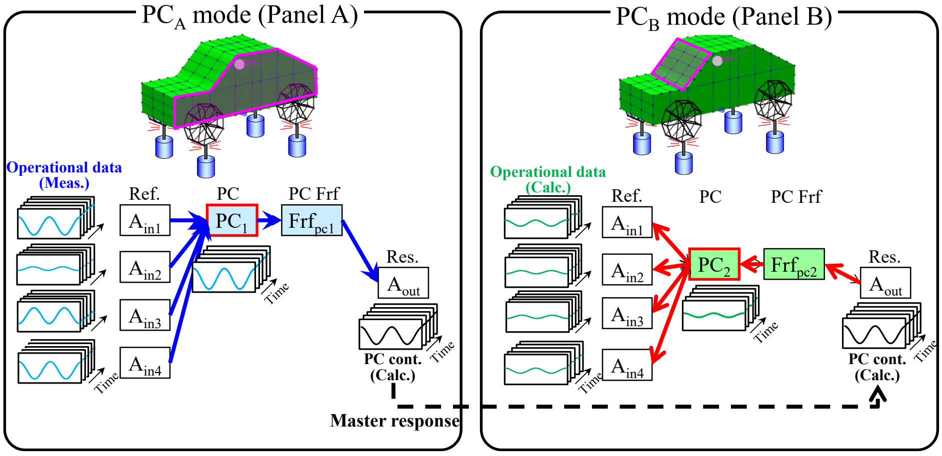


Fig. 11 Estimation of the PC level and reference signal using master response.

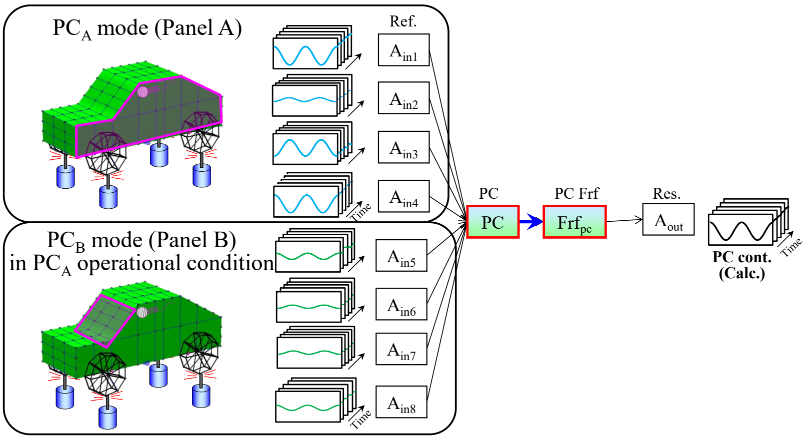
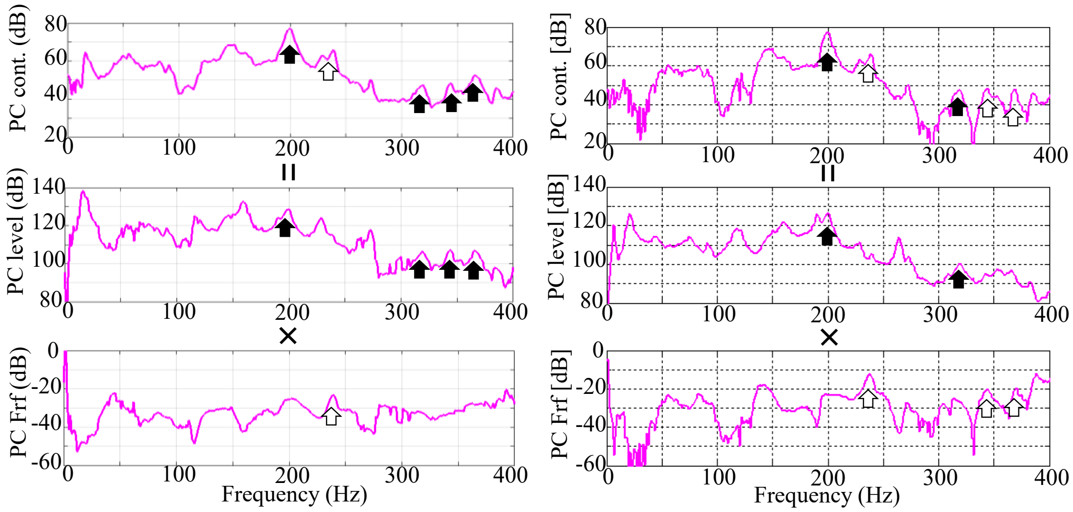


Fig. 12 Calculation of whole body PC level and PC transfer function.

4.4 Obtained integrated whole body PC level and PC transfer function

The above mentioned method was applied to the separated measurement signals. In this case, the data set acquired under the operational test for the left side panel was used as the master data. Figure 13 (a) shows the integrated high contributing PC level, PC transfer function, and the contribution of whole body panel, respectively. Figure 13 (b) shows the partial PC1 level, PC1 transfer function and the contribution in case the PC contribution analysis was applied to the data of the left side panel for comparison.



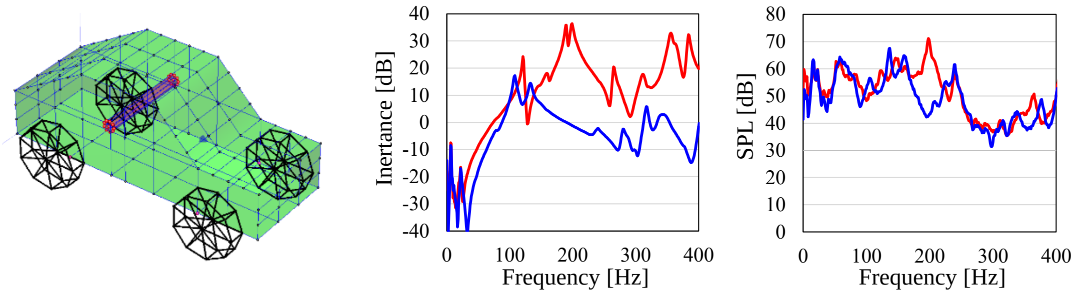
(a) PC contribution of whole body (b) Partial PC contribution of left side panel

Fig. 13 PC level, PC transfer function and the contribution in each condition.

As shown in the Fig. 13 (b), PC level and PC contribution (response signal) were observe to have several vibration or SPL peaks at similar frequency bands (200 Hz and 320 Hz) as indicated by filled arrows. This means PC of the target structure (left side panel) increased the interior noise. On the other hand, PC transfer function was found to be the main factor to increase the interior noise at the other frequencies (240, 340 and 370 Hz,) as shown in opened arrows. In this case, it is hard to estimate which part (vibration of the other panels or resonance in cabin) increased the interior noise. On the contrary, as shown in Fig. 13 (a), most interior noise peaks are observed to be made by the integrated whole body PC level (200, 320, 340, 370 Hz) except for 240 Hz. In addition, the number of the peak of the PC transfer function of the whole body (Fig. 13 (a)) was found to be smaller than that of the partial PC transfer function (Fig. 13 (b)). This means that including factors in the PC transfer function decreased in the integrated whole body transfer function and finding the main factor increasing the interior noise became easier by the proposed procedure. In the next section, we attempted to decrease the interior noise at the target frequency (200 Hz) by using this analytical result.

5. INTERIOR NOISE REDUCTION

The whole body PC level had peak at 200 Hz as same as the interior noise. Hence, the vibration characteristic of the body was considered to be the main factor generating the interior noise peak. In addition, the high contributing integrated whole body PC mode at 200 Hz was shown to have large vibration at the center of left and side panels along the opposite direction. Then, we performed a countermeasure considering the high contributing PC mode shape to verify whether the integrated whole body PC mode had actually large influence on the interior noise. In this instance, we inserted a steel bar between the center of the left and right panels to constrain the oppositely movement of the side panels as shown in Fig.14 (a).



(a) Countermeasure *(b) Point inertance of left side panel* *(c) Interior noise SPL*

Fig. 14 Countermeasure image and the effect of the countermeasure.

After inserting the steel rod, we carried out impact measurement test to obtain point inertance at the left panel center and also performed operational test again at the same condition to record interior noise before and after the countermeasure. Figure 14 (b) and (c) shows the point inertance comparison and the interior SPL comparison by the impact hammering test and the operational test, respectively. As the results, the point inertance at the left side panel was observed to decrease largely at wide frequency band over 150 Hz as shown in Fig. 14 (b), but the interior noise was found to decrease largely only at 200 Hz band (reduction target frequency) as shown in Fig. 14 (c). This reveals that the side panel vibrated at the wide frequency band but the side panel vibration affects largely to vehicle interior noise only at 200 Hz band, hence the interior noise at 200 Hz was mainly decreased by the countermeasure. From these results, these integrated whole body PC modes was clarified to have large influence on the interior noise at 200 Hz actually.

6. SUMMARY

In this study, we proposed a method to integrate high contributing PC mode of the whole body and the PC contribution to the interior noise using PC contribution analysis through separated measurements. In the method, the high contributing whole body PC mode was obtained by using the correlation of each partial PC with the response signal. And the phase and amplitude relationship between them were compensated using the unit response signal. The obtained whole body PC mode was confirmed to indicate the global vibration mode of the target structure under the operational condition in a few modes. In addition, the whole body PC level and the PC transfer function to the interior noise was also estimated by using the master data at an operational test to find out the factor increasing the interior noise in detail. As the result, we could estimate the main factor of the interior noise through relationship among the whole boy PC contribution, the PC level and the PC transfer function. Finally, the obtained high contributing whole body PC mode was verified to have large influence on the interior noise actually through the countermeasure instance.

From these results, this PC contribution analysis can be applied if we cannot prepare large measurement system and sensors adequate for the simultaneously measurement to all reference points by carrying out the separating measurements. And the method could extract high contributing global vibration mode excited at the operational condition and giving large influence on the interior noise for the effective countermeasure.

7. ACKNOWLEDGEMENTS

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