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Analytical method for vehicle interior noise using principal component contribution

-Identification of resonance frequency in cabin at the operational condition utilizing principal component transfer function-

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ABSTRACT

Principal component (PC) contribution analysis utilizing operational TPA was developed to evaluate high contributing vibration behavior of the target structure such as vehicle body. However, not only the vibration characteristic but also acoustic characteristic in cabin had better to be focused for more effective countermeasure. In this study, we attempted to identify the main factor increasing the interior noise between body vibration and cabin acoustic characteristics. In the test, a simple vehicle model was employed and vibration at multiple points around the body and interior noise were measured. Subsequently, PC contribution to the interior noise was calculated by multiplying PC level and PC transfer function. We then focused the PC level and the transfer function of the highest PC contribution. We estimated if the PC level was large, the interior noise was increased by the vibration characteristic. On the other side, if the PC transfer function was large, the noise was increased by the acoustic characteristic (resonance) in cabin. According to the above consideration, we actually applied a countermeasure to change the resonance frequency in cabin because the PC transfer function increased the interior noise. As the result, the interior noise at the target frequency could be decreased very well.

Keywords: Operational TPA, Principal component analysis, Resonance frequency
I-INCE Classification of Subject Number: 74, 75

1. INTRODUCTION

For carrying out effective countermeasure to reduce the interior noise of vehicle, finding out the contribution of each sound or vibration source to the interior noise is essential. Transfer path analysis (TPA) has been proposed to obtain the contribution quantitatively and several methods were developed until now[1-6]. Operational TPA (OTPA) is one of the methods recently developed which enable us to obtain the contribution of each sound and vibration sources to interior noise for a short period to

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calculate the contribution using only the sound and vibration signals at the operational condition[2,4-6]. In general OTPA method, the reference points were set at close of the force input point such as the suspension attachment point to obtain the high contributing point to the interior noise. On the other hand, in case we obtain the high contributing vibration behaviour (vibration mode), a new method utilizing OTPA calculation procedure (PC contribution analysis) was proposed recently[7,8]. In this method, the reference points are set around the target structure where we focused such as vehicle body, and the PC of the target structure vibration and the PC transfer function to the interior noise are calculated. Through the method, we can extract high contributing vibration mode to the interior noise. On the other hand, interior noise was not increased only by vibration mode of vehicle body, but the acoustic characteristic in cabin also may increase the noise by the resonance.

In this study, we then considered a method for identifying the main factor between the body vibration or resonance in cabin that increases the interior noise by evaluating the PC and the transfer function. In addition, we attempted the interior noise reduction considering the analytical result and utilizing CAE technique as the verification.

2. CALCULATION PRPCEDURE OF OTPA[2,4-8]

In the original OTPA, the transfer function of each reference point to the response point is calculated by applying PC regression method using only simultaneously measured reference and response signals at the operational condition as shown in Fig. 1. The contribution of each reference point to the response point is obtained by multiplying each reference signal with the transfer function.

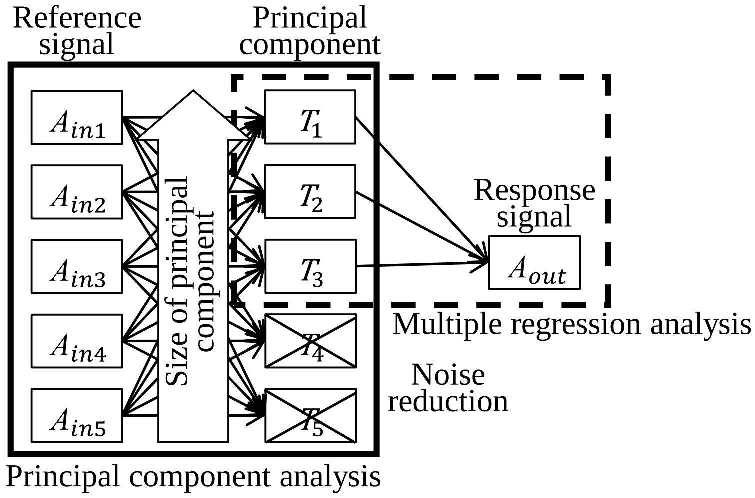


Fig. 1 Calculation procedure of operational TPA

Detailed calculation procedure of OTPA is described as follows.

Firstly, reference and response signals are measured at the operational condition and carry out frequency analysis by applying FFT repeatedly. Secondly, PC analysis is applied to the reference signal matrix $[A_{in}]$ by singular value decomposition (SVD) to extract correlation among reference signals for obtaining PC $[T]$ as shown in Eqs. (1) and(2).

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

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

Here, the noise component having very low level are eliminated. And multiple regression analysis is applied between the remind (signal) PCs $[T]$ and the response signal

$[A_{out}]$ to obtain the influence coefficient $[B]$ of each PC to the response signal as shown in Eqs. (3) and (4).

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

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

In addition, transfer function from reference signal to response signal $[H_A]$ is calculated by multiplying the coefficient $[V]$, that connects PC and response signal as shown in Eq. (5)

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

Finally, the reference point contribution and PC contribution to the response point are calculated by using $[H_A]$ or $[B]$ as shown in Eqs. (6), (7) respectively.

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

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

These are the outlines for obtaining contributions by OTPA. In this study, we focused on the PC contribution as shown in Eq. (7) to consider analytical method for identifying the main factor between the body vibration and resonance in cabin that increases the interior noise by evaluating the PC and the transfer function.

3. PC CONTRIBUTION ANALYSIS TO SIMPLE VEHICLE MODEL

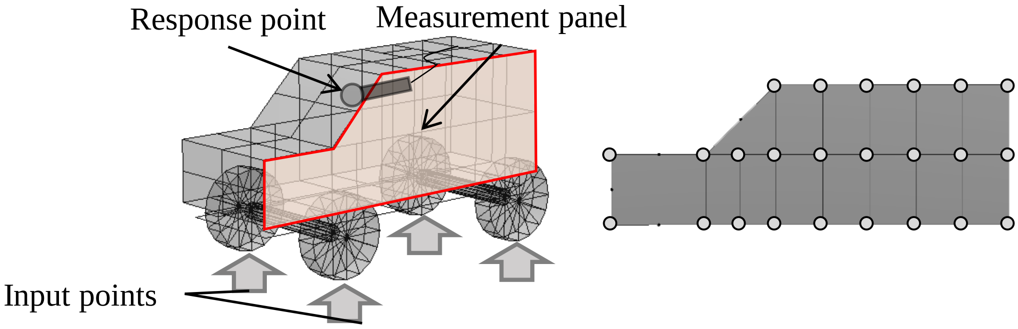
3.1 Operational test

For the operational test, a simple vehicle model was made as shown in Fig. 2. The vehicle model consisted of body, frame and four tires. The length, width and height of the body and the frame were 850×300×300 mm, 850×300×20 mm, respectively. Total weight of the model was 26 kg. The thickness of the body panel and the material were 3 mm and Alminum, respectively. The cavity surrounding by the panels was regarded as the vehicle interior.

Fig. 2 Simple vehicle body model employed in this study

In this operational test, four electrical magnetic exiters (Modalshop: K2007E01) were put under the four tires to give random input signals for 50 s. As the response point signal, vehicle interior noise was recorded by microphone set in cabin as shown in Fig. 3(a). As the reference points, a lot of vibration signals around the body panel had better to be measured simultaneously to obtain PC contribution of the body structure.

However, unrealistic number of the measurement points have to be necessary if we apply the method to the actual vehicle according to the vehicle size and the measurement system. Therefore, separated measurement method for the PC contribution anlaysis was employed in this study[9]. For applying the method, the measurment was iterated in total 8 times in each body panel. In the measurment, identical response point signal (interior noise) was recorded in all measurements and the reference point number varied from 9 to 24 as shown in Fig. 3(a). Figure 3(b) shows the instance of the reference point on the left side panel where 24 reference points were set.



(a) Response and input points *(b) Reference points at left side panel*

Fig. 3 Experimental condition

3.2 PC contribution to the interior noise

By applying the PC contribution analysis to the separated measured analysis, we obtained the PC contribution of the body structure to the interior noise. Figure 4 shows the interior noise recorded at the condition where the reference points were set on the left side panel.

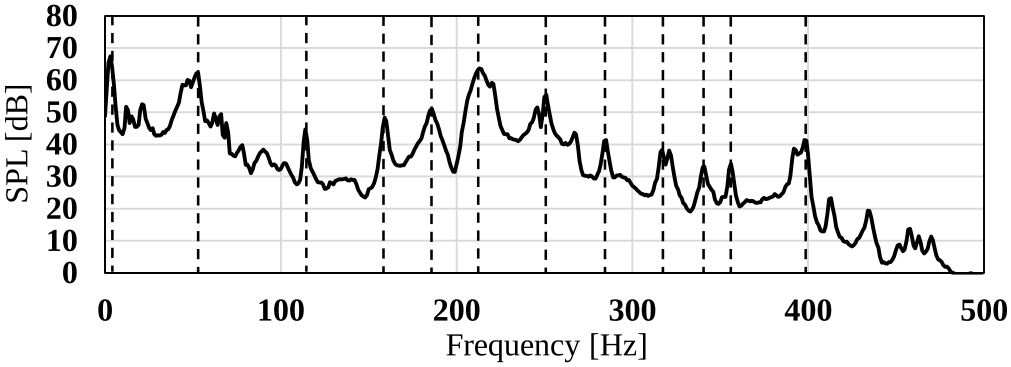


Fig. 4 Sound pressure level of interior noise

As shown by dotted black lines in the figure, the SPL was found to have large peak at many frequency bands such as 212 Hz. Here, we focused on the factor of the large SPL higher than 100 Hz, because the human perception to the sound is known to be low sensitive under 100 Hz. Accordingly, we attempted to identify the main factor of the large SPL at the target frequency band over 100 Hz in the following analyses. We calculated the PC contribution of the whole body panel using the separated measurement reference point signals to the interior noise to identify the main factor increasing SPL peaks. Figure 5 shows the averaged actual interior noise, high contributing PC contributions, PC and PC transfer function of the body structure, respectively.

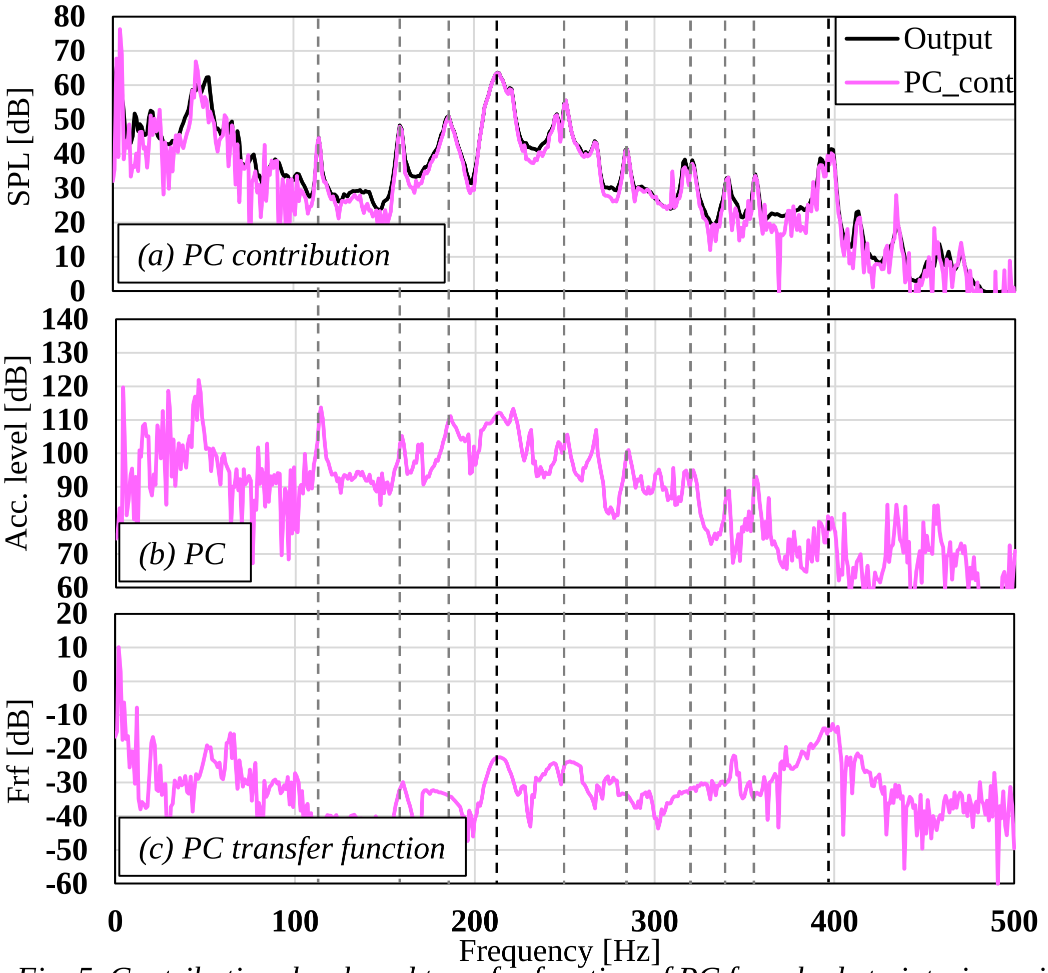


Fig. 5 Contribution, level, and transfer function of PC from body to interior noise

As shown in the upper figure, the high contributing PC contribution and the actual interior noise were almost same level. This indicates that the PC contribution dominated the interior noise and the reduction of this PC contribution makes the interior noise reduction effectively. Subsequently, PC and PC transfer function, which composed the PC contribution (PC x PC transfer function = PC contribution), were evaluated to identify the main factor increasing the SPL. As the result, most SPL peaks were observed to be made by the PC itself (114, 160, 186, 251, 285, 320, 335 and 355 Hz) because PC had the similar peak with the contribution as shown in Fig. 5(b) and (a). This means that the interior noise was increased by the vibration characteristic (vibration mode) of the body structure. On the other hand, the PC transfer function at around 212 and 400 Hz were found to make the SPL peak as shown in Fig. 5(c) where both interior noise SPL and PC transfer function had the peaks. This situation indicates that the acoustic characteristic (resonance) in cabin was an important factor increasing the interior noise. From these results, we could estimate the main factor increasing interior noise between body panel vibration and resonance in cabin by evaluating PC contribution.

4. RESONANCE FREQUENCY IN CABIN

4.1 Evaluation of the resonance frequency through acoustic test

Acoustical test was carried out to obtain resonance frequency in cabin. For evaluating the resonance frequency, we compared recorded sound pressure levels in two conditions where the sound was recorded without cabin (Fig. 6 (a)) and the sound was recorded in cabin (Fig. 6 (b)). As the sound source, a speaker (JBL: JBLGO2BLK) was employed and random noise from 0 to 500 Hz was reproduced for 10 s. The resonance frequency in cabin was evaluated using the acoustic transfer function obtained by dividing the SPL in cabin (Fig. 6 (b)) by the SPL without cabin (Fig. 6 (a)).

(a) Opened space *(b) In cabin*

Fig. 6 Experimental condition for obtaining acoustic transfer function

Figure 7 shows the obtained acoustic transfer function.

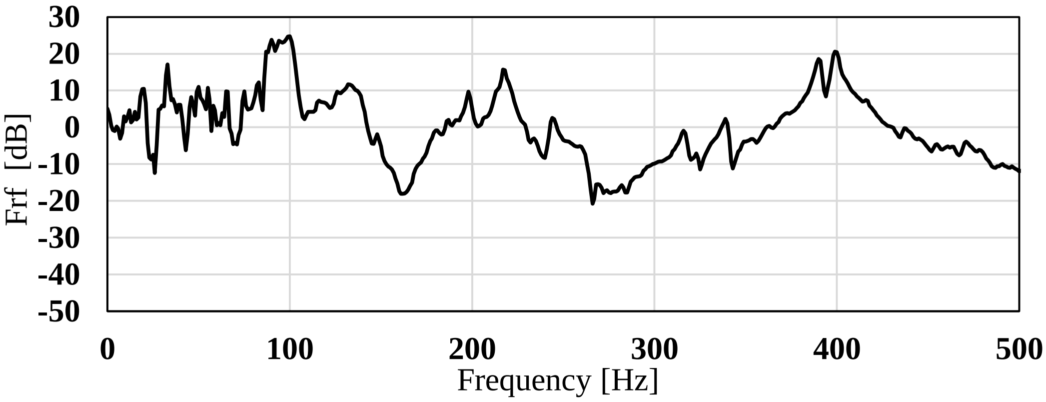


Fig. 7 Acoustic transfer function in cabin

As shown in the figure, the acoustic transfer function has large level at 217 and 399 Hz over 100 Hz. These frequency were almost same at the peak frequencies of PC transfer function as shown in Fig. 5 (c). This result means that in case the PC transfer function is the main factor of the interior noise peak, the acoustic resonance in cabin increases the interior noise as estimated in the previous section. And the proposed method using PC contribution was verified to have the possibility to estimate the main factor of the interior noise in cabin correctly.

4.2 Acoustical mode in cabin increasing interior noise at operational condition

In the previous section, high contributing acoustic characteristic (resonance frequency) in cabin was clarified. For carrying out effective countermeasure at the frequency, acoustic mode at the resonance frequencies had better to be known, hence, eigenvalue analysis was carried out by using CAE. For the simulation model, identical materials and dimension of cabin were prepared by using first order solid model including 64080 elements and 69688 nodes as shown in Fig. 8.

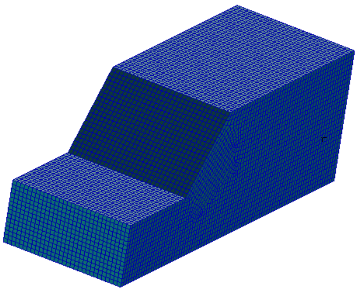
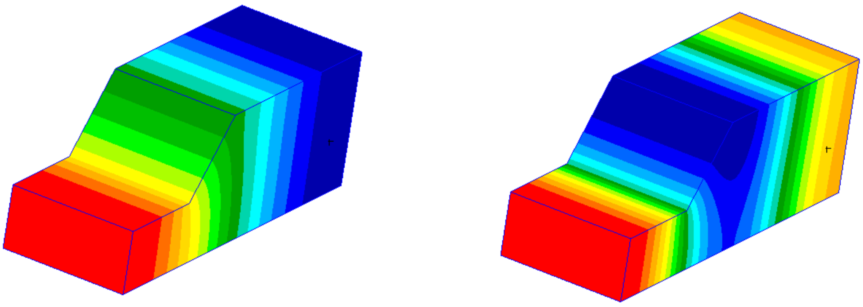


Fig. 8 Cabin model of vehicle body on CAE

As the result of eigenvalue analysis, natural frequencies (resonance frequency) in cabin were calculated as to be 216 and 376 Hz from 100 to 500 Hz and the mode were shown in the Fig. 9.



216 Hz 376 Hz

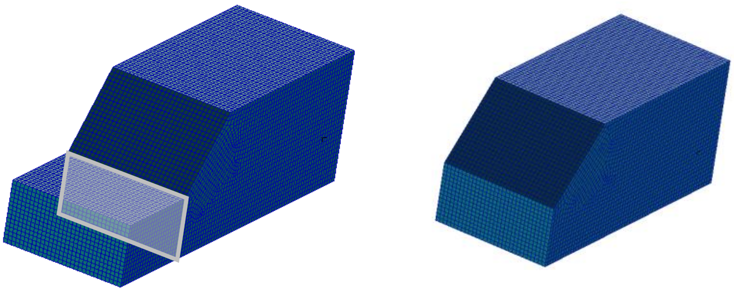
Fig. 9 Acoustic mode shapes obtained by CAE from 100 Hz to 500 Hz

As shown in the upper figure, the acoustical mode shapes were the first and second modes along longitudinal direction. The acoustic resonance frequencies in cabin obtained by CAE were almost same as the acoustic transfer function obtained in the acoustic test (Fig. 7) and the peak of the PC transfer function (Fig. 5 (c)). This indicates the acoustical modes of these frequency were the main factor increasing the interior noise at the operational condition. Accordingly, carrying out countermeasure considering these modes were expected to decrease the interior noise effectively.

5. COUNTERMEASURE TO THE INTERIOR NOISE CONSIDERING HIGH CONTRIBUTING ACOUSTIC MODE

5.1 Considering countermeasure to high contributing acoustic modes

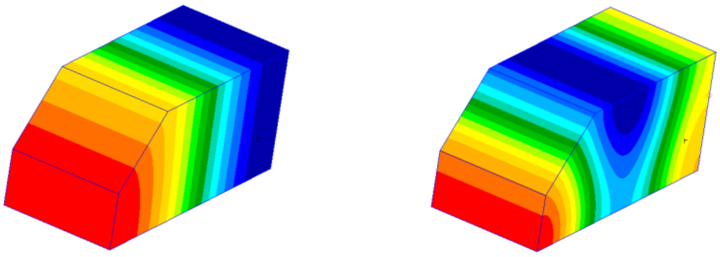
In the previous section, high contributing acoustic modes were found using OTPA with PC model and eigenvalue analysis of CAE. In this section, we attempted to decrease the interior noise at the resonance frequencies considering the high contributing acoustic modes. The acoustical modes were the first and second mode along longitudinal direction, hence, the volume of the cabin was separated into two spaces as shown in Fig. 10 (a). Then, eigenvalue analysis was again performed to the separated spaces as shown in Fig. 10 (b) to check the change of the resonance frequency of the modified model.



(a) Countermeasure part *(b) Modified model*

Fig. 10 Countermeasure considering high contributing acoustic mode

As the result, the natural frequencies and the acoustic modes of the modified model were obtained as shown in Fig. 11.



274 Hz 518 Hz

Fig. 11 Acoustic mode shapes of the modified mode

As shown in Fig. 11, the natural frequencies in cabin were increased to 274 and 518 Hz, where the interior noise of the original vehicle model was small or the frequency is out of the target frequency band (100 to 500 Hz). This tendency indicates that the interior noise at the target frequency band will be decreased by applying countermeasure.

5.2 Change of the resonance frequency by the modification

For applying the countermeasure to the experimental model considering the CAE result, we inserted a plastic plate to separate cabin in vehicle model into two spaces as indicated in Fig. 10. Subsequently, acoustical test was again carried out under the same condition to clarify the influence of the modification. The obtained acoustical transfer function before and after the countermeasure were shown in the Fig. 12. The black solid and red dotted curves show the acoustical transfer function before and after the countermeasure, respectively.

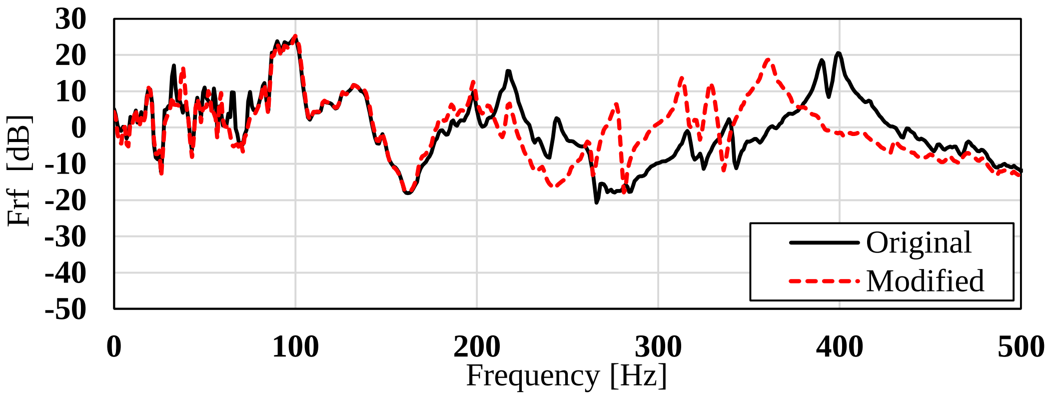


Fig. 12 Comparison of acoustic transfer function before and after countermeasure

As shown in the upper figure, the acoustical transfer function was confirmed to change and the transfer function level at the focused frequency band (210 and 400 Hz), where the resonance in cabin increased the interior noise, decreased.

5.3 Effect of the countermeasure on interior noise at operational condition

After confirming the resonance frequency change by separating the cabin space, the interior noise at the operational condition was recorded again before and after the countermeasure to grasp the influence of the separating the cabin space on the interior noise at the operational condition. The operational test condition was the same as the operational test for the original model described in Sec. 3.1. Figure 13 shows the comparison of the interior noise at the operational condition before and after the countermeasure. The black solid and red dotted curves show the SPL of interior noise before and after the countermeasure, respectively.

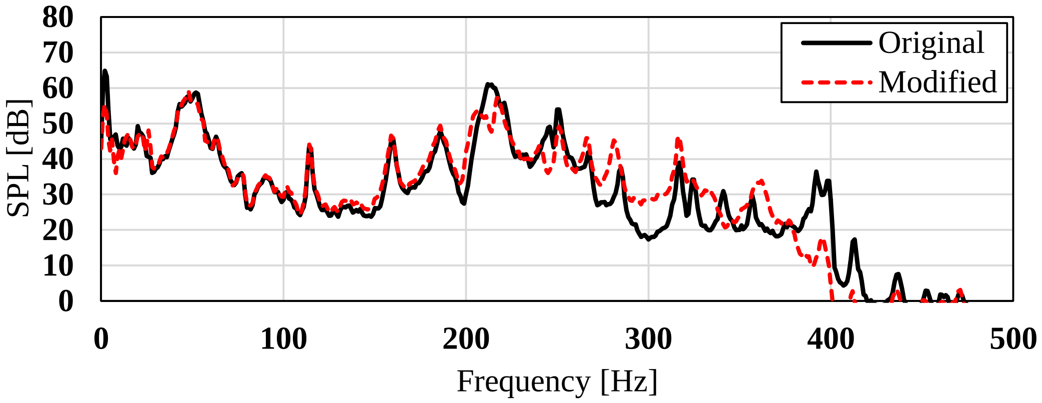


Fig. 13 Comparison of interior noise before and after countermeasure

As shown in the figure, SPL of the interior noise at around 210 and 400 Hz band was found to decrease well. This shows that the proposed method utilizing OTPA with PC model could indicate the main factor (resonance in cabin) accurately, and effective countermeasure way also can be obtained using CAE to the high contributing acoustic characteristic in cabin.

6. SUMMARY

In this study, we developed a method to identify the main factor of the interior noise SPL at the operational condition between the vibration characteristic of the body structure and the acoustic characteristic of cabin utilizing the PC contribution and considered the effective countermeasure way at the target frequency where the acoustical characteristic of cabin was the factor using CAE eigenvalue analysis. At first, operational experiment was carried out using simple vehicle model, PC contribution analysis was applied between vehicle body vibration at multiple points and the interior noise. The result shows PC transfer function was observed to make the interior noise peak at several frequency bands. In addition, acoustical characteristic in cabin was estimated to be the main factor increasing the interior noise at the frequency bands. Then, the acoustical mode shape in cabin at the frequency was obtained by CAE eigenvalue analysis. Finally, the interior noise at the operational condition could be decreased well at the target frequencies by applying intensive countermeasure to the acoustical phenomena in cabin and the effectiveness of proposed method was verified.

7. ACKNOWLEDGEMENTS

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8. REFERENCES

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