PROCEEDINGS of the
23rd International Congress on Acoustics

9 to 13 September 2019 in Aachen, Germany

Obtaining method of high contributing body and frame vibration behavior to road noise using principal component contribution analysis

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ABSTRACT

Principal component (PC) contribution analysis utilizing operational TPA (OTPA) was developed to find out high contributing vibration behavior of the target structure to the interior noise. However, in case a vehicle is composed of body and frame, identifying the high contributing part between them is difficult using this method. In this study, we then attempted to propose an identification method of the high contributing part between body and frame using OTPA sequentially. In the test, a simple vehicle model having body and frame was employed and vibration at multiple points on the body and frame were measured simultaneously with the interior noise when random input signals was given. Subsequently, OTPA were applied in two steps. In the first step, high contributing body vibration behavior to the interior noise was extracted and then, high contributing frame vibration reference point to the important body mode was also obtained in the second step. From these results, we estimated the main part increasing the interior noise at the target frequency bands. Finally, the interior noise could be decreased by applying intensive countermeasure according to the analytical results.

Keywords: Operational TPA, Contribution, Road noise

1. INTRODUCTION

For carrying out effective countermeasure to vehicle interior noise, finding out main contributing sound or vibration source and the transfer path is essential. Transfer path analysis (TPA) (1-8) was proposed to obtain the contribution quantitatively. Operational TPA (OTPA) (6-8) is one the methods recently developed and it calculates the contribution using only the sound and vibration signals at around input points (reference signals) and the interior noise (response signal) under the operational condition. This method is utilized not only in the vehicle development but also the other products such as home appliances. In these days, modified OTPA method (OTPA with principal component (PC) (8) model) has also been developed for obtaining the important vibration behavior of the target structure such as vehicle body to the interior noise by analyzing the PC mode of the structure on the contrary to the reference (Ref) model which calculates each reference point contribution to the response point in the original OTPA. On the other side, in case the target vehicle has sub-frame or frame component, the vibration input from the engine or tire is decreased by the rubber bushes between the input part and the frame. In addition, the vibration of the frame is also decreased by the other rubber bushes between the frame and the body. In this case, the information about which part between frame and body should be measured intensively becomes important for carrying out more effective countermeasure. Applying OTPA PC model to the simultaneously measured all reference signals both at body and frame side is considered for the method. However, if the stiffness of the body is relatively lower than the frame, the body vibration becomes much larger than the frame vibration. And the high contributing PC mode (vibration behavior of the body and the frame) is determined mainly by the body vibration. Hence, it is hard to understand the high contributing part of the frame and evaluating which part between body and frame should be measured intensively is also hard.

In this study, we then considered to apply the OTPA PC model and Ref model sequentially between interior noise and vehicle body to obtain high contributing body vibration behavior (PC mode) and between the high contributing body PC and the frame points to clarify which part (body and frame) is the main factor generating large interior noise and the countermeasure part.

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2. CALCULATION OF REFERENCE AND PC CONTRIBUTION BY OTPA

2.1 Reference and PC contribution calculation

In the original operational TPA, 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 principal component regression method. The calculation procedure is followings.

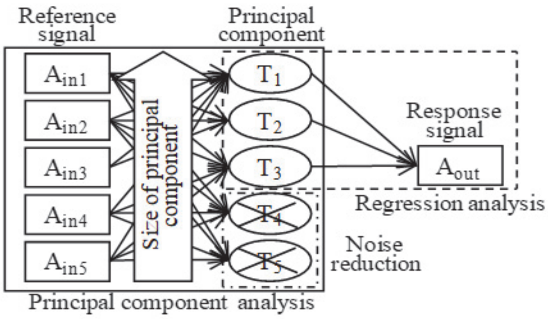


Figure 1 – Calculation image of transfer function of original OTPA using principal component regression method

PC analysis is firstly applied to the reference signal matrix $[A_{\text{in}}]$ 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 $[A_{\text{in}}]$ 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 $[A_{\text{in}}]$ is the data at the j-th reference point in the i-th FFT. Matrices $[U]$, $[S]$, and $[V]$ are obtained by SVD. $[V]$ is the coefficient matrix to transpose the reference matrix $[A_{\text{in}}]$ 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 $[A_{\text{out}}]$ to obtain influence $[B]$ of each PC to the response signal as shown in Eqs. (3) and (4).

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

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

The (i,m)-th element in the response matrix $[A_{\text{out}}]$ 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)

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

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. This is the outline for obtaining both contributions by OTPA. In this study, we utilized both PC contribution (PC model) as shown in Eq. (7) and reference point contribution (Ref model) as shown in Fig. (6) to obtain important vibration behavior and the part for the reduction of the interior noise.

2.2 High contributing PC mode

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 reference signal and the PC can be developed as follows (Eq. (9)). Noting that the reference number is reduced to two for simple explanation.

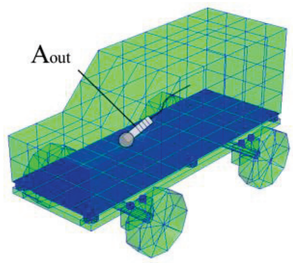
$$\begin{bmatrix} a_{11} & a_{12} \\ a_{21} & a_{22} \\ \cdot & \cdot \\ a_{n1} & a_{n2} \end{bmatrix} = \begin{bmatrix} t_{11}v_{11} + t_{12}v_{12} & t_{11}v_{21} + t_{12}v_{22} \\ t_{21}v_{11} + t_{22}v_{12} & t_{21}v_{21} + t_{22}v_{22} \\ \cdot & \cdot \\ t_{n1}v_{11} + t_{n2}v_{12} & t_{n1}v_{21}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

In Eq. (9), 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 PC1 elements. By using this information, the vibration behavior of each principal component in each reference point of the target structure can be observed. This behavior is the principal component mode in OTPA. If the principal component has high contribution to the response point, the PC mode is the high contributing PC mode and the response point signal is expected to decrease efficiently by applying intensive countermeasure to the mode.

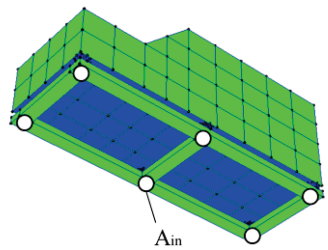
3. STEPWISE APPLICATION OF OTPA PC MODEL & REF MODEL

In this study, we attempt to clarify which part between the body and the frame should be measured intensively for the reduction of the interior noise, that has double anti-vibration system by applying stepwise OTPA PC and Ref models. Here, we describe how we estimate the main factor of the interior SPL peak according to the stepwise OTPA application results.

Figure 2 shows an image of the measurement points for the stepwise application. Figure 2 (a) shows the reference and response point for the OTPA PC model in the first step. In the first application, the interior noise is used as the response signal and the multiple vibration acceleration signals around the body (cross points in Fig. 2 (a)) are used as the reference signals. Figure 2 (b) shows the image of the second OTPA Ref model. In the second application, the response points are set as the same point of the reference points in the first application. The reference points are set at around the rubber bush attachment points on the frame. In the operational test, all signals for the first and second analyses are recorded simultaneously but the analysis is separated.



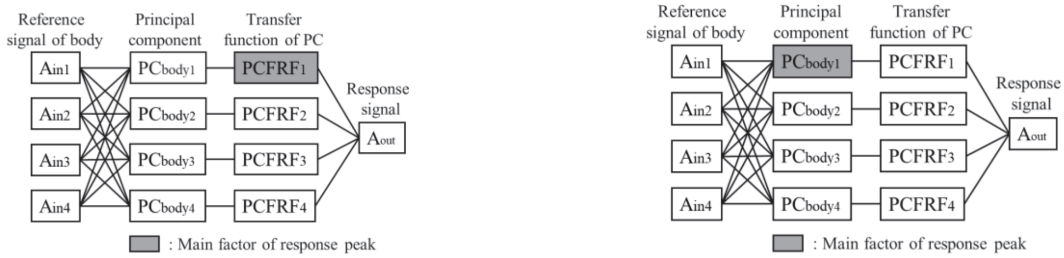
(a) OTPA PC model between body and interior noise



(b) OTPA Ref model between frame and body

Figure 2—Image of the vibration and sound measurement points for stepwise application of OTPA

After the operational test, the body vibration signals and the interior noise signal are used for the first analysis as shown in Fig. 2 (a). The estimated main factors of the interior noise peak according to the first analytical result using OTPA PC model are shown in Fig. 3 (a) and (b).



(a) Case 1: Body PC transfer function makes SPL SPL peak in cabin.

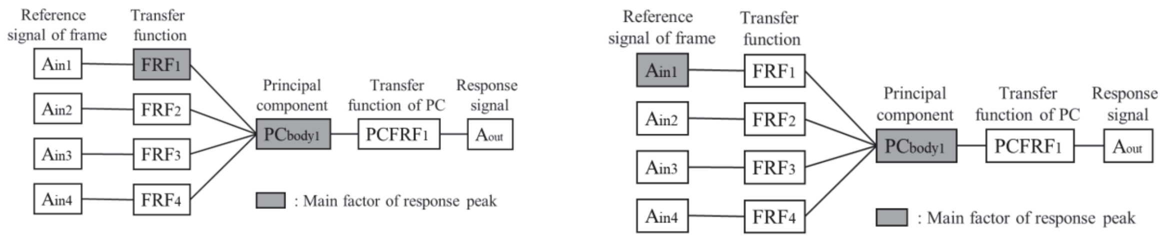
(b) Case 2: Body PC is the main factor of SPL peak in cabin.

Figure 3－Analytical result image of OTPA PC model in first analysis.

1) In case PC transfer function from the body vibration PC to interior noise makes SPL peak in cabin as shown in Fig. 3 (a), the body vibration is not the main factor but the transfer function from the body to interior noise such as the resonance in cabin seems to be the main factor (9). Hence, countermeasure to the cavity is effective way to reduce the interior noise.

2) In case the body vibration PC makes the SPL peak in cabin as shown in Fig. 3 (b), the vibration characteristic of the body is the main factor. If we can constrain the important vibration behavior (high contributing PC mode) of the body, the interior noise is expected to decrease effectively. However, we cannot determine whether the high contributing body vibration is increased by the resonance of the body part or is not increased but by the large vibration from the frame.

Then, we apply the second OTPA Ref model between the high contributing body PC and the vibration signals of the frame at around the rubber bush attachment points to estimate the main factor of the high contributing body PC signal. In the analysis, the high contributing body PC obtained by the first OTPA PC model is used as the response signal and the vibration signals of the frame are used as the reference signal as shown in Fig. 2 (b). The reason why OTPA PC model is not employed in the second analysis is due to the importance of the vibration transferring points from the frame. Even though we find large vibration behavior of the frame at the target frequency through OTPA PC model, it is not necessary to apply any countermeasure to the frame if the vibration behavior does not have large amplitude at the rubber bush attachment points (reference points in the second analysis) on the frame. Hence, we apply OTPA Ref model for the analysis. The estimated main factor of the SPL peak in cabin according to the second analytical result is shown in Fig. 4.



(a) Case 3: Transfer function from frame to body makes high contributing body PC peak.

(b) Case 4: Frame vibration is the main factor of the high contributing body PC.

Figure 4－Analytical result image of OTPA Ref model in second analysis.

3) In case transfer function from the frame to the body makes the body PC peaks as shown in Fig. 4 (a), this indicates the frame vibration is not the main factor but the vibration is increased at the body side. Hence, the countermeasure had better to apply to the body side for the reduction of the interior noise according to the high contributing body PC mode obtained in the first analysis.

4) In case the frame vibration has peak and this makes the high contributing body PC and SPL peaks in cabin as shown in Fig. 4 (b), the high contributing body PC is considered to be made by the frame vibration at the bush attachment points. Therefore, the countermeasure should be applied to the high contributing reference point according to the OTPA Ref model.

We applied this procedure actually to a simple vehicle model and estimated the main factor of the interior noise peak according to the stepwise OTPA application results in the next section.

4. EXPERIMENT USING SIMPLE VEHICLE MODEL AND STEPWISE APPLICATION OF OTPA PC MODEL & REF MODEL

4.1 Operational test

For the operational test, a simple vehicle model was employed as shown in Fig. 5 (a). 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, 850×300×5 mm, respectively. Total weight of the model was 26 kg. The thickness of the body panel and the material were 3 mm and Aluminum, respectively. And the thickness of the frame and the material were 5 mm and Aluminum. In this experiment, an operational test imitating a vehicle running on a rough road was carried out to obtain the vehicle body, frame vibration and the interior noise. Four electrical magnetic exciters (Modalshop: K2007E01) were attached to the lower part of each tire as shown in Fig. 5 (a) and random signal under 400 Hz assuming road noise inputs were given to the vehicle body.

(a) Vehicle model (b) Measurement points

Figure 5 —Experimental model

As the response point signal, vehicle interior noise was recorded by a microphone set in cabin as shown in Fig. 5 (b). As the reference points, a lot of vibration signals around the body and the frame had better to be measured simultaneously, however, according to measurement system and the number of sensors what we had, only the floor panel (15 points) and frame (6 points) were used as the reference signals in this experiment as shown in Fig. 5 (b).

4.2 STEPWISE APPLICATION OF OTPA PC MODEL & REF MODEL

4.2.1 Obtaining of high contribution PC of floor panel to the interior noise

As the first step, we obtained the PC contribution of the floor panel to the interior noise by applying the PC contribution analysis between interior noise and the vibration signals of floor panel as shown in Fig. 6. Upper diagram in Fig. 6 shows the PC1 contribution and the interior noise. As shown in the figure, the PC1 contribution was found to have the largest contribution. Middle and lower diagrams of the figure shows the PC1 transfer function and PC1 level that compose the PC1 contribution.

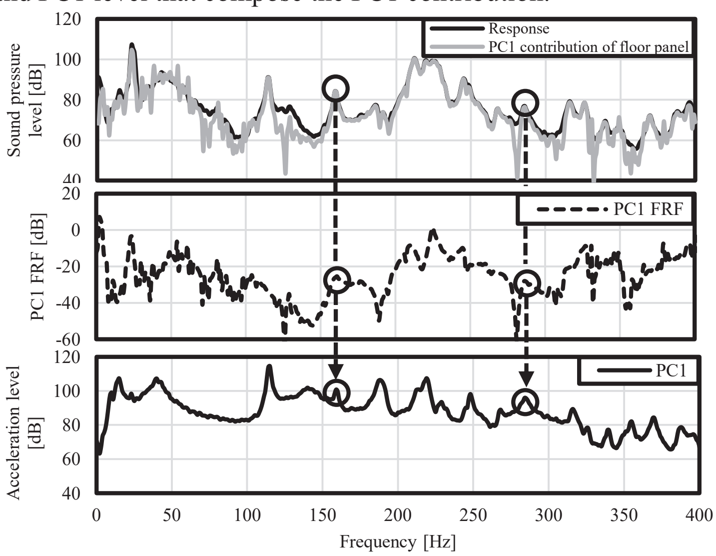


Figure 6—PC1 contribution and the elements

As shown in the figure, PC1 contribution and interior sound peaks at 200-250 Hz band was observed to be made by the PC1 FRF level peak. Hence, the large interior sound peak at the frequency band was estimated to be made by the acoustic resonance in cabin (9). In addition, the large interior sound peak 160 Hz and 280 Hz was considered to be made by the large vibration of the floor panel because the large PC1 peak was observed at the same frequency band. Then, as the second step, we estimated whether the main contribution of the floor panel vibration (PC1) to the sound at 160 Hz and 280 Hz bands were increased by the resonance of floor panel itself or by the large vibration from the frame. For evaluating it, we applied OTPA Ref model between the high contributing body PC1 and the vibration signals of the frame at around the six rubber bush attachment points. Figure 7 shows the calculated contribution from each reference point to the high contributing body PC.

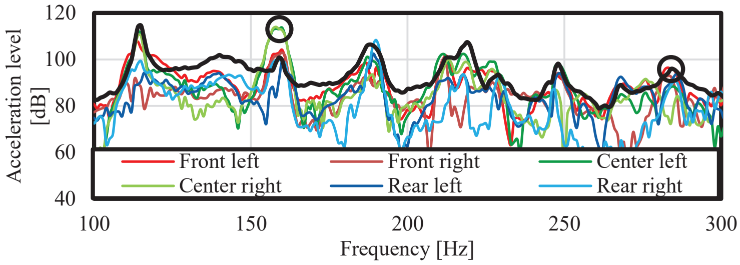


Figure 7—Contribution of each reference point of frame to high contributing floor PC1.

As shown in Fig. 7, the central attachment points at the frame were observed to be dominant contribution at around 160 Hz. On the other hand, front and rear attachment points were observed to have large contribution at around 285 Hz. Then, we compared the reference signal level and the transfer functions at large contribution points as the second step. The comparison of transfer function and reference signal at central attachment points around 160 Hz were shown in Fig.8.

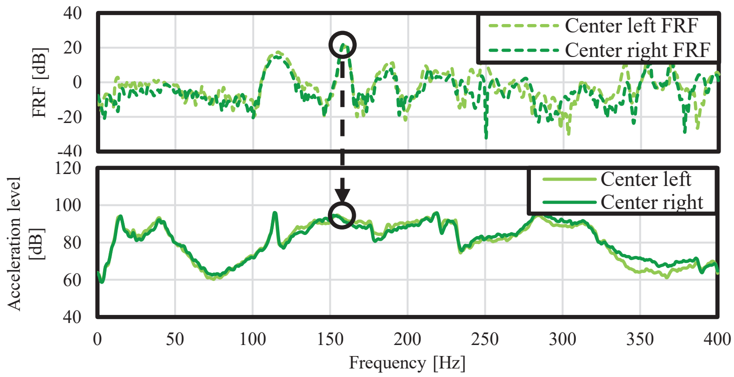


Figure 8—Transfer function and reference signal at central attachment points.

As shown in Fig. 8, FRF of central attachment points was found to have peak at around 160 Hz. Hence, the large interior sound peak at 160 Hz was estimated to be made by the resonance of floor panel. Here, the high contributing PC mode at 160 Hz of the floor part was extracted by the firstly applied PC contribution analysis. The obtained PC1 mode was shown in Fig. 9.

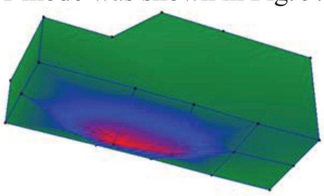


Figure 9—High contributing PC mode of floor panel at 160 Hz

As shown in Fig. 9, the high contributing PC mode of floor panel was the behavior having large vibration amplitude at around central front point. Hence, applying modification to the point was considered to be the effective countermeasure to reduce the interior sound. Subsequently, transfer functions and the reference signal vibration acceleration levels of rear attachment points of the frame at around 285 Hz were shown in Fig. 10.

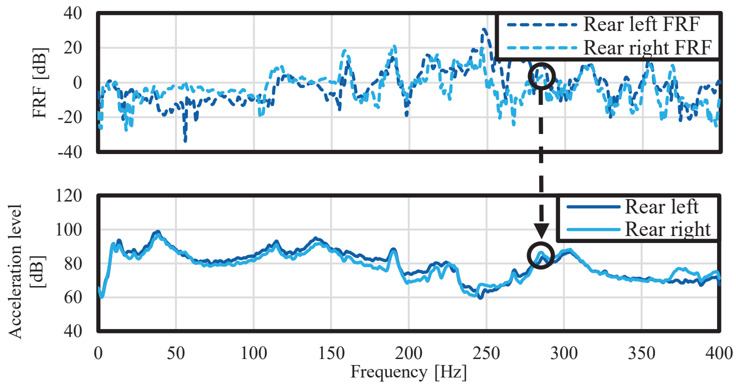
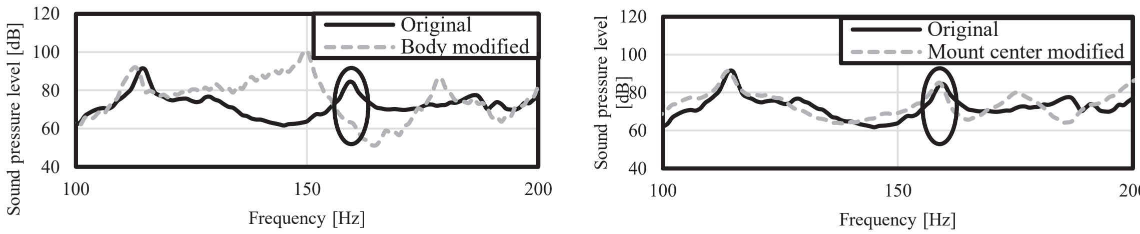


Figure 10 — Transfer function and reference signal at rear attachment points of the frame.

As shown in Fig. 10, reference signal was observe to have peak at 285 Hz. Hence, the interior sound at the frequency band was estimated to be made by the large vibration at the rear frame.

5. INTERIOR NOISE REDUCTION CONSIDERING ANALYTICAL RESULTS OF STEPWISE OTPA

The factor of interior sound peaks were estimated at the target frequency bands, respectively through the stepwise OTPA. The body side was the main factor at 160 Hz band and the frame side was the factor at 285 Hz band. We then performed countermeasure considering these analytical results to verify the estimated the factors. As the countermeasure to the interior sound at 160 Hz band, we added total 300 g weight according to the obtained high contributing floor PC mode as shown in Fig. 9. Operational test was carried out again at the same condition with the previous test and the interior noise was recorded before and after the countermeasure. Figure 11 (a) shows the comparison of the interior sound at the operational condition before and after the countermeasure to the body side. For the verification of the effectivity of the countermeasure to the body side, we also added the weight at the center attachment points of the frame side having largest contribution among frame instead of the body side. Figure 11 (b) shows the comparison of the interior sound before and after the countermeasure to the attachment points.



(a) Modification to the high contributing PC mode of the

(b) Modification to the high contributing reference points of

Figure 11 — Comparison of interior sound before and after countermeasure

As shown in Fig. 11 (a), the interior sound decreased largely at 160 Hz by applying the countermeasure to the body side. On the other hand, the interior sound was not decreased by the countermeasure to the high contributing part of the frame side as shown in Fig. 11 (b). These results reveals that the proposed method utilizing the stepwise application of OTPA PC model and Ref model could indicate the main factor correctly and the countermeasure should be applied to the main factor between body and frame side for the effective reduction of the interior noise. In addition, we also performed a countermeasure considering analytical results at 285 Hz. In this frequency band, the frame vibration at rear points were one of the main factor increasing the interior sound at the frequency band. Then, we added total 300 g weight to the rear input points of the frame side and carried out the same operational test. Figure 12 shows the comparison of the interior sound before and after the countermeasure to the frame side.

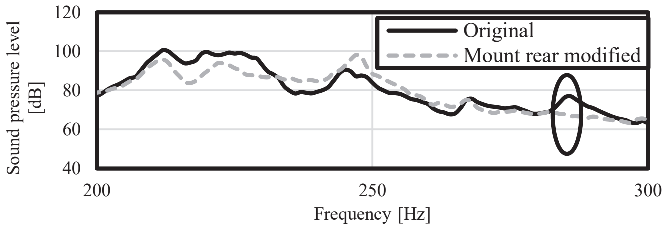


Figure 12—Comparison of interior sound before and after countermeasure

As the result, the interior sound was also observed to decrease at 285 Hz by the countermeasure. From the above analytical and experimental results, we could clarify the main factor increasing interior sound between body and frame sides for the effective interior noise reduction by using stepwise application of OTPA PC model and Ref model.

6. CONCLUSIONS

In this study, we attempted to clarify which part between the body and the frame should be measured intensively for the reduction of the interior noise having double anti-vibration system by applying stepwise OTPA PC and Ref models. In the experiment using a simple vehicle model, an operational test imitating the vehicle running on a rough road was carried out. Then, we estimated the main factors of the interior sound peak at the target frequency bands between body side and the frame side using stepwise application of OTPA PC model and Ref model. In the first analysis, OTPA PC model was applied between interior sound and body vibration and OTPA Ref mode was carried out between the high contributing body PC and the frame vibration. From the analytical results, the large interior sound peak at 160 Hz was estimated to be made by the resonance of the body side. On the other side, the large interior sound peak at 285 Hz was observed to be made by the large frame vibration. For the verification of these results, we carried out countermeasure considering the analytical results. As the results, the interior sound could be decreased well in case we applied the countermeasure to the estimated important part on the body side or frame side. From these results, the proposed method was clarified to have the ability to indicate which part between body and frame side is the main factor increasing interior sound and the intensively measured part of the system.

ACKNOWLEDGEMENTS

The authors thank Mueller-BBM in Germany and TOYO cooperation in Japan for supporting this work.

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