PROCEEDINGS of the
23rd International Congress on Acoustics

9 to 13 September 2019 in Aachen, Germany

Transfer Path Analysis of Rumbling Noise in a Passenger Car Based on Measured In-Situ Blocked Force'

Sang Kwon LEE[1], Tejin SHIN, Yeonsoo KIM, Kanghyun AN

[1] Inha University, South Korea

ABSTRACT

The control of rumbling noise is one of the major strategic targets of interior sound quality inside the cabin of a passenger car. To effectively control rumbling noise in a passenger car, the transfer path of the rumbling noise should be initially identified. It is known that the major source of this noise the combustion force of an engine. The combustion force excites the engine and induces vibrations of the powertrain. These vibrations are then transferred to the body of the vehicle via its structural transfer path. Moreover, the vibrations of the vehicle's body emit internal vibra-acoustic noise. This noise is often referred to as the rumbling noise due to the structural borne path. If there are structural resonances among the structural paths such as the engine, transmission, mount bracket, suspension, and the vehicle's body, the rumbling noise could be amplified. To identify the major resonances of the structural transfer path, classical transfer path analysis (CTPA) has been traditionally utilized. The method has a significant limitation in that it is necessary to decouple the substructures to obtain the contact force between individual components and to identify the transfer path of the structure-borne sound. Recently, blocked force transfer path analysis (BF-TPA) was introduced and this approach does not require the decoupling of the substructures. In this study, we identify the structure-borne path of rumbling sound based on blocked force transfer path analysis (BF-TPA) in a passenger car. In addition to identification, the passive control method for rumbling sound is presented.
Keywords: Blocked force, Transfer path analysis, Rumbling noise, Powertrain, Interior Noise

1. INTRODUCTION

In order to improve the perception of the sound quality of rumbling noise, passive methods have been traditionally used [1]. Noise radiated from the powertrain is an airborne source of rumble noise inside a vehicle. A few examples of major airborne sources of noise in a car include intake noise, exhaust noise, and the radiation noise of powertrain components including the cylinder block, oil pan, front cover etc. The vibration of the powertrain is induced by combustion forces. The combustion force transfers to the mounts of the powertrain through the transfer path such as the crankshaft train, main bearings, cylinder block and housing of the transmission. The force transferred to the mounts excites the car vehicle's body and induces vibrations. These vibrations, in turn, generate vibro-acoustic rumble noise inside the car. This is the structure-borne path of rumble noise which is often quite complex. As a classic method to identify the structure-borne noise, classic transfer path analysis (CTPA) is used [2]. This method uses the contact force between the powertrain and the car's body at the mount points. The contact force can be measured using various approaches and depends on the condition of the subsystem such as the mount bracket and the car's body. In order to measure the contact force, the powertrain and the body of the car should be disconnected. This requires tedious work and is time intensive. The contact force should be changed as a result of changes to the boundary condition due to the disconnection. Blocked force transfer path analysis (BF-TPA) was recently introduced. This method involves the measurement of the blocked force of the main system at the contact point of this system and the subsystem. This method does not require the disconnection of both systems. The blocked force of the main system is independent of the condition of the subsystem [3]. BF_TPA has been applied to automobile engineering to overcome the difficulty associated with using CTPA. This method has been applied to identify the transfer path of road noise and the contribution of the suspension mount system to the road noise [4]. In addition, BF_TPA has also been applied to the

1 sangkwon@inha.ac.kr

study of the transfer path of the steering system and other major sources of interior noise associated with the power steering system [5]. Validation of the blocked force method for various boundary conditions was investigated and applied to identify the blocked force on the suspension system of the electric vehicle [6]. A comparison between BF-TPA path, CTPA, and operational transfer path (OTPA) methods have been investigated for an electric vehicle [7]. In this study, the BF-TPA method was investigated to obtain the blocked force of a powertrain at mount positions, with the goal of identifying the contribution of each mount to rumble noise [8]. Finally, the identified transfer components were modified and their effect on the reduction of rumble noise was validated base on the modulation index.

2. THEORY OF TPA

2.1 CTPA

Let us consider a vehicular system as shown in Fig.1. The system is composed of two subsystems. System A is the powertrain and system B is the car's body as shown in Fig. 2. Both systems are connected by several mounts.

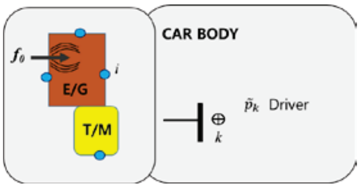

Figure 1. Car system composed of a powertrain system A and car body system B.

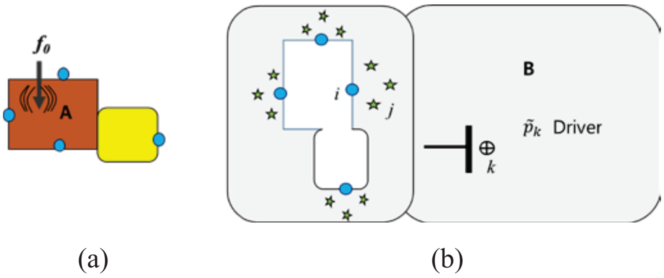

Figure 2. Separated car system (a) subsystem A is the powertrain and (b) subsystem B is the car's body.

In order to predict the interior noise due to the structure-borne transfer path, CTPA has been traditionally used and its mathematical expression is given by,

$$\tilde{\mathbf{p}}_k^{AB} = \mathbf{H}_{ki}^{B}\mathbf{f}_i \tag{1}$$

where $\mathbf{H}_{ik}^{B}(\omega)$ with units Pa/N is the noise frequency response function (NFRF) of system B between the mount point at position i and the driver's seat at position k under the condition of disconnection with system A, $\mathbf{f}_i$ is the operating contact force at the mount point at position i and $\tilde{\mathbf{p}}_k^{AB}$ is the estimated sound pressure at the driver seat at the k position due to the number of structure-borne paths under the coupled condition of system A and system B. System A is the source of rumble noise and is excited by the internal force $\mathbf{f}_o$ when the combustion of the engine is initiated. Therefore, international force $\mathbf{f}_o$ is correlated with the combustion force. This force is transferred to the mount position. The operating contact force $\mathbf{f}_i$ at the i mount point acts on system B, which is the receiver. The operating contact force can generally be obtained using the stiffness inverse method and is mathematically given by:

$$\mathbf{f}_i = \left[\mathbf{Y}_{ij}^{B}\right]^{-1}\mathbf{v}_j^{B} \tag{2}$$

where $\left[\mathbf{Y}_{ij}^{B}\right]$ is the mobility with unit ms-1 /N between the i-th mount point and the driver seat at the j-th position under the condition of being disconnected with system A. $\mathbf{v}_j^B$ is the operating velocity at the j-th indicator position of system B under the condition of being connected to system A, and is given by:

$$\mathbf{v}_j^B = \left[\mathbf{Y}_{ij}^B\right]\mathbf{f}_i \tag{3}$$

2.2 In-Situ BF-TPA

The blocked forces are the forces required to prevent any vibration of the source. In practice, the direct determination of these values is a very difficult task since the process requires an infinitely stiff receiver structure. However, the blocked forces can be determined theoretically in an indirect manner for a receiving structure with no specific requirements.

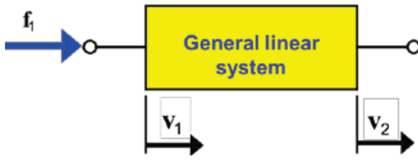

Figure 3. Multiple inputs and multiple outputs for a linear system

According to the mobility theory for a linear system as shown in Fig.3, the equations that describe the system are given by

$$\begin{bmatrix} \mathbf{v}_1 \\ \mathbf{v}_2 \end{bmatrix} = \begin{bmatrix} \mathbf{Y}_{11} & \mathbf{Y}_{12} \\ \mathbf{Y}_{21} & \mathbf{Y}_{22} \end{bmatrix} \begin{bmatrix} \mathbf{f}_1 \\ \mathbf{f}_2 \end{bmatrix} \tag{4}$$

where $\mathbf{Y}_{ij}$ is the mobility for the velocity response $\mathbf{v}_j$ with respect to input force $\mathbf{f}_i$. Based on this theory, a coupling system such as the car system examined in this investigation is shown in Fig.1. The major advantage of the BF-TPA is that theoretically, it does not impose any specific requirements while CTPA requires the decoupling of system B from system A to facilitate measurement of the noise transfer function $\mathbf{H}_{k,i}^B(\omega)$ and the mobility function $\mathbf{Y}_{i,j}^B(\omega)$. The velocity vector $\mathbf{v}$ can be expressed by:

$$\begin{bmatrix} \mathbf{v}_o^A \\ \mathbf{v}_i^A \\ \mathbf{v}_i^B \\ \mathbf{v}_k^B \end{bmatrix} = \begin{bmatrix} \mathbf{Y}_{oo}^A & \mathbf{Y}_{oi}^A & 0 & 0 \\ \mathbf{Y}_{io}^A & \mathbf{Y}_{ii}^A & 0 & 0 \\ 0 & 0 & \mathbf{Y}_{ii}^B & \mathbf{y}_{ik}^B \\ 0 & 0 & \mathbf{Y}_{ki}^B & \mathbf{Y}_{kk}^B \end{bmatrix} \begin{bmatrix} \mathbf{f}_o \\ \mathbf{f}_i^A \\ \mathbf{f}_i^B \\ 0 \end{bmatrix} \tag{5}$$

In this case, the upper part is related to the mobility of the powertrain system A, and the lower part is related to that of the car body system B. In order to couple both subsystems, the boundary condition at the interface position i should be satisfied as follows:

Velocity condition: $\mathbf{v}_i^A = \mathbf{v}_i^B$ (6.a)

Force condition: $\mathbf{f}_i = \mathbf{f}_i^A = -\mathbf{f}_i^B$ (6.b)

The vibration response at position k in the system B can be expressed by the blocked force $\mathbf{f}_i^b$, which is applied to the coupled system AB at position i. It is given mathematically by:

$$\mathbf{v}_k^B = \mathbf{Y}_{ki}^{AB}\mathbf{f}_i^b \tag{7}$$

From Eq. (7), Eq. the blocked force can be expressed as:

$$\mathbf{f}_i^b = \left(\mathbf{Y}_{ii}^A\right)^{-1}\mathbf{Y}_{io}^A\mathbf{f}_o \tag{8}$$

The acoustic response at the k position is given by:

$$\tilde{\mathbf{p}}_k^B = \left[\mathbf{H}_{ki}^{AB}\right]\mathbf{f}_i^b \tag{9}$$

where $\mathbf{H}_{ki}^{AB}$ is the coupled noise transfer function with units Pa/N. As previously mentioned in this section, since the direct measurement of the blocked force is a very difficult task, indirect measurement can be obtained by substituting the measured operating velocity at the indicator points j of system B into Eq. (7), similar to the case shown in Fig. (2),

$$\mathbf{f}_i^b = \left[\mathbf{Y}_{ij}^{AB}\right]^{-1} \mathbf{v}_j^B \tag{10}$$

3. APPLICATION OF IN-SUIT BF-TPA TO RUMBLE NOISE

3.1 Description of a test vehicle and measurement equipment.

The test vehicle is an economy-sized car with a 1.5-liter gasoline engine. Fig 4 shows the arrangement of the powertrain on this vehicle and the sensors used to measure the interior sounds and vibrations. The test car was accelerated from 1000 rpm to 6000 rpm under a wide open condition of the throttle body. The sensor used for the measurement of the interior noise was a 1/2 inch microphone (Bruel & Kjaer, 4506). The microphone was installed at the driver' ear position. For the measurement of the motility functions between the mount positions and the indicator positions, the impact hamper (PCB, 086C03) was used to excite the indicator positions and three indicator accelerometers (Endevco, 65HT 10704) per mount were used to measure the vibrations at the mount positions of the body side under the coupled condition of the powertrain and body. The indicator positions are presented with 9 red color points as shown in Fig. 4.

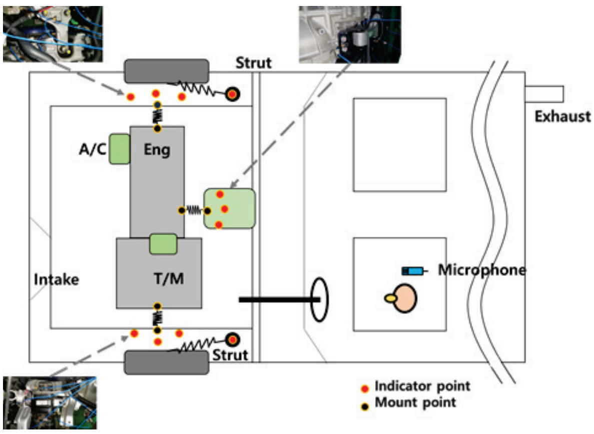

Figure 4. Scheme of the test vehicle and the position of the sensors attached to the test vehicle to measure the interior sounds and vibrations.

The operating vibration at the nine indicator positions was also measured during the acceleration. For the measurement of the noise frequency function $\mathbf{H}_{ki}^{AB}$, the acoustic source (LMS, Low-frequency Q-source) was installed at the driver seat and tri-axial accelerometers (Endevco, 65HT 10704) were attached at each mount position for the measurement of the vibration of the body side and engine side. A total of 6 block color points in Fig. 4 identify these mount positions. Data acquisition was performed by the data acquisition system (LMS, Mobile) with sampling at 2048 Hz.

3.2 Problem definition

Interior noise was measured using a microphone located at the driver's seat position as shown in Fig.4. Fig.5 shows a color map for the interior sound measured inside of the test vehicle during acceleration. Heavy rumbling noise at the frequencies of 450 Hz and 590 Hz was detected as shown in Fig.5. Rumbling sound occurred due to the modulation of the harmonic orders of the rotating frequency of the engine's crankshaft. C1.5, C3, C4.5 and C6 denote the number of harmonic orders. The objective of this investigation was to reduce the rumbling noise and improve the perception of rumbling sound quality.

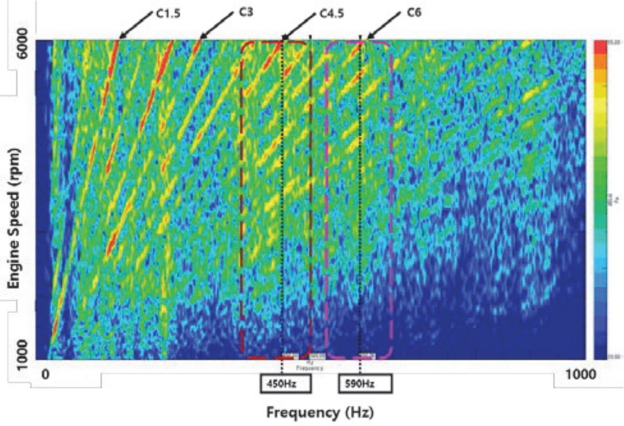

Figure 5. Spectrogram of the interior noise measured at the driver ear position inside of the test vehicle.

3.3 Estimation of the interior noise based on In Suit BF-TPA

The interior noise was estimated using Eq. (9), based on the In-Suit BF-TPA method. Fig. 6 shows a comparison of the measured interior noise with the interior noise estimated using the In-Suit BF-TPA method in the frequency band of rumble noise. According to these results, there is a difference between the measured noise and the estimated noise above 3500 rpm as shown in Fig. 6(a). The estimated rumble noise is the only due to structure-borne path. Therefore, the difference is due to the airborne path. In particular, the effect of the airborne path in the frequency band at 590 Hz is more significant than in the case of the 450 Hz band, as shown in Fig. 6(b) and (c). Considering the latter, the structure-borne path is dominant compared to the airborne path below 4500 rpm as shown in Fig. 6(b). The modification of the structure-borne path can reduce rumble noise at a frequency band of 450Hz. This modification can improve the perceived sound quality of the interior noise.

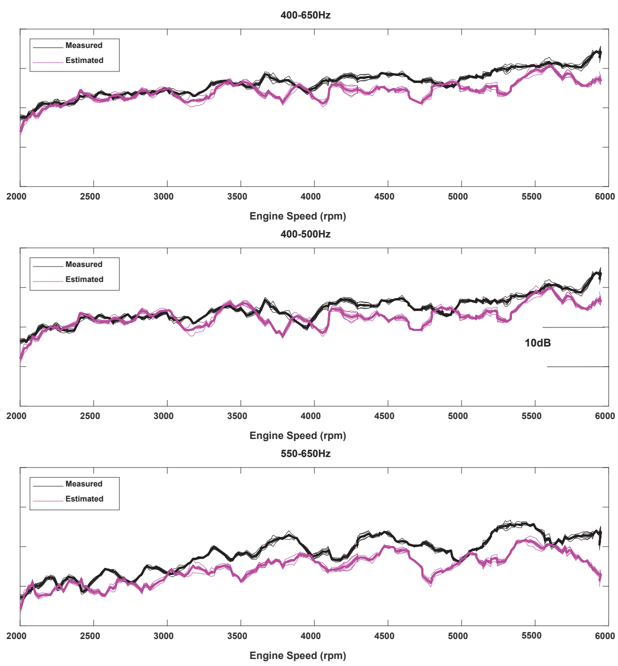

Figure 6. Comparison of the measured interior noise with the interior noise estimated using the In-Suit BF-TPA method for the frequency band (a) 400-650 Hz (b) 400-500 Hz (c) 550-650 Hz

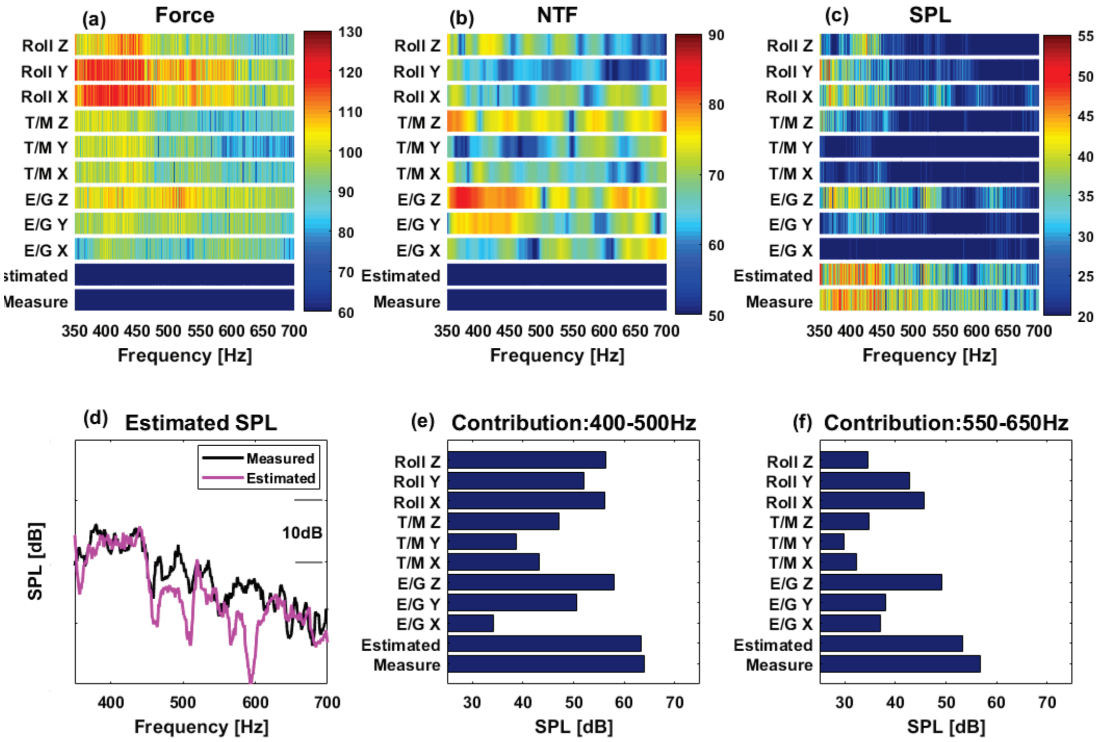

Figure 7. Contribution analysis for transfer path of rumbling noise based on In Suit BF-TPA at an engine speed of 3000 rpm.

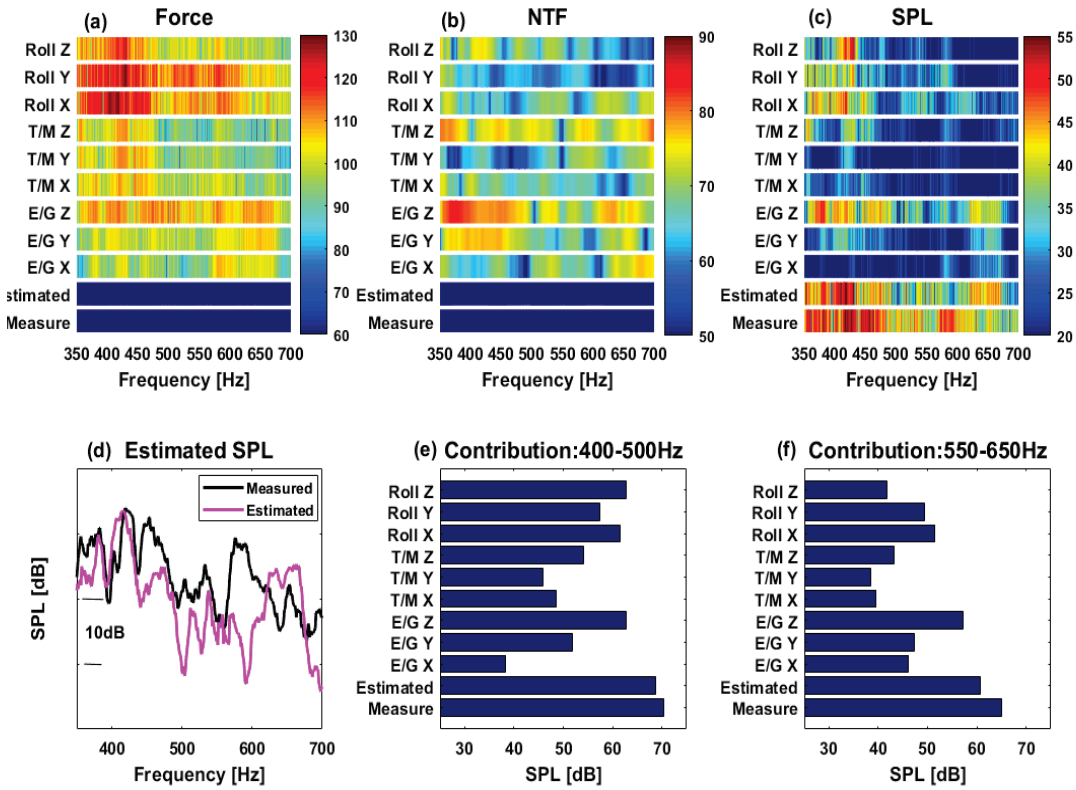

Figure 8. Contribution analysis for transfer path of rumbling noise based on In Suit BF-TPA at an engine speed of 5500 rpm.

For the modification of the structure-borne path, the contribution of the paths should be identified. Fig. 7 shows the contribution of the structure-borne paths of the rumbling noise at 3000 rpm. The blocked force is dominant at the roll mount in all direction and the engine mount in the z-direction is shown in Fig. 7(a). The noise transfer function of the car's body shows that the engine mount is a major path in the z-direction as shown in Fig. 7(b). Therefore, the sound pressure contribution of each path is plotted as shown in Fig. 7(c). The major path contribution to rumble noise in the frequency range at approximately 450 Hz is the engine mount in the z-direction and the roll mount in all directions as shown in Fig. 7 (d) and (e). Even at approximately 590 Hz, these two paths are important as shown in Fig. 7 (f). Fig. 8 shows the contribution of the structure-borne paths of the rumbling noise at 5500 rpm. The blocked force is dominant at the roll mount in all direction and the engine mount in the z-direction is shown in Fig. 86(a). The major transfer paths of the structure-borne rumbling noise are the engine mount in the z-direction and the roll mounts, similar to those at 3000rpm as shown Fig. 86(c). At a frequency of approximately 590 Hz, the measured noise is higher than the estimated noise as shown in Fig. 8 (d) and (f). This noise level difference is due to the airborne path.

4. FEASIBILITY TEST

Fig. 9 shows the frequency spectrum for the time-averaged data at approximately 3000 rpm. From these results, it can be concluded that the added mass was effective in reducing the structure-borne noise in the frequency range from 400 Hz to 500 Hz at engine speeds of 3000 rpm.

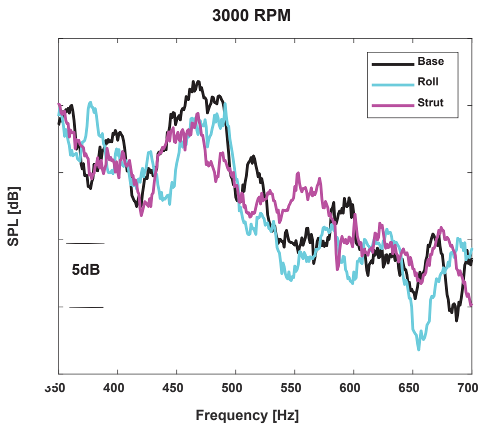

Figure 9. Effect of added mass on rumbling noise based on spectrum analysis for the time averaged data at approximately 3000 rpm

5. CONCLUSIONS

This investigation involved an examination of the theoretical difference between CTPA and In Suit BF-TPA. The CTPA method utilizes contact forces at the mount position while In Suit BF-TPA uses blocked forces. The blocked force is independent of the structure of the car's body. In view of the intended application, the difference of both methods is a coupling condition of powertrain with car' body. The CTPA method requires a decoupling of the source and receiver to measure the contact force and to predict the vibration and noise at the target point on the receiver. However, In Suit BF-TPA does not require a decoupling. This is an advantage because the disconnection of the source and receiver results in lost time and causes a change in stiffness of the system. Finally, Suit BF-TPA was utilized to identify the transfer path of the rumbling noise and the structure-borne path of the rumbling was well identified.

ACKNOWLEDGEMENTS

This work was supported by Mid-career Researcher Program through NRF of Korea grant funded by the MEST (No. 2016R1A2B2006669)."

REFERENCES

1. Beranek LL. Criteria for noise and vibration in buildings and communities. In: Beranek LL, Ver IL, editors. Noise and Vibration Control Engineering - Principles and Applications. 2nd ed. New York, USA: Wiley; 2006. p. 887-909.
2. Widrow B, Stearns SD. Adaptive Signal Processing. Englewood Cliffs, New Jersey, USA: Prentice-Hall; 1985. 1. Lee, S. M., Park, D. C., Kim, S., Lee, S. K., A Novel Method for Objective Evaluation of Interior Sound in a Passenger Car and Its Application to the Design of Interior Sound in a Luxury Passenger Car. SAE International 2017, 2017-01-1758, 2017
2. Gajdatsy, P., Janssens, K., Desmet, W., Auweraer, H.V.D., Application of the transmissibility concept in transfer path analysis. Mechanical Systems and Signal Processing 24, 1963- 1976, 2010.
3. Moorhouse, A. T., Elliott, A. S., Evans, T. A., In situ measurement of the blocked force of structure-borne sound sources. Journal of Sound and Vibration 325, 679–685, 2009.
4. Elliott, A.S., Moorhouse, A.T., Huntley, T., Tate, S., In-situ source path contribution analysis of structure borne road noise. Journal of Sound and Vibration, 332 6276–6295, 2013.
5. Alber, T., Sturm, M., Moorhouse, A.T. (2016). Independent characterization of structure-borne sound sources using the in-situ blocked force method, Proceeding of Internoise 2016.
6. Lennström, D., Wullens, F., Olsson, M., Nykänen, A., Validation of the Blocked Force Method for Various Boundary Conditions for Automotive Source Characterization. Applied Acoustics 102, 108-119, 2016.
7. Diez-Ibarbia, D., Battarra, M., Palenzuela, J., Cervantes, G., Walsh, S., De-la-Cruz, M., Theodossiades, S., Gagliardini, L. (2017). Comparison between transfer path analysis methods on an electric vehicle. Applied Acoustics, 118, 83–101.
8. Shin, T., Kim, Y., An, K., Lee, S. K., Article title: Transfer Path Analysis of Rumbling Noise in a Passenger Car Based on In-Situ Blocked Force Measurement Article reference, Applied Acoustics, 149, 1-14, 2019.