공학석사 학위논문

A Study of a Representative Input Point Selecting Method at Multiple Coupling Mounts for Road Noise Transfer Path Analysis

로드노이즈 전달경로분석을 위한 다중결합 지점에서의 대표 입력점 선정 방법

2021 년 8 월

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이 논문을 공학석사 학위논문으로 제출함

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ABSTRACT

A Study of a Representative Input Point Selecting Method at Multiple Coupling Mounts for Road Noise Transfer Path Analysis

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The recent implementation of more stringent regulations on automobile emission has led to the increasing proportion of eco-friendly cars in the automobile market. With the development of eco-friendly vehicles, electric systems using motors and batteries have been gradually applied to automobile systems. Technological changes have shifted the interest of researchers from engine noise to road noise transmitted from the road surface to the vehicle's interior. Consequently, the estimation and analysis of road noise during driving has become a relevant task in the initial development phase of automobiles. In this study, methods for improving the estimation accuracy of road noise using transfer path analysis (TPA) is proposed. The main road noise transfer path is the mount connecting the suspension to the body. The suspension mounts consist of single and multiple bolted joints. In general, when estimating road noise using TPA, an arbitrary bolt is referenced as the input load transfer path at the mount where multiple bolts are fastened. In this case, depending on the selected mounting bolt, the reduction in the road noise reproduced in the rumble frequency domain (250–500 Hz) can be observed. To improve the accuracy in reproducing noise in the rumble frequency domain, virtual points are created and reflected in the road noise TPA using the data derived around the mounts.

In this work, virtual point transformation and central difference method are applied as data post-processing techniques for creating virtual points. Thereafter, the estimated results are compared with those obtained using conventional TPA methods.

Keyword : Transfer Path Analysis (TPA), Frequency response function (FRF), Road noise, Virtual Point Transformation (VPT), Central Difference Method (CDM), Suspension mounts

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CHAPTER 1. INTRODUCTION

1.1. STUDY BACKGROUND

With the recent enforcement of more of environmental laws, the regulations on automobile emissions have also become more stringent. These emission regulations have shifted the direction of automotive R&D from diesel-based and gasoline-based internal combustion engines to electrified systems. Moreover, the application of electrified systems to vehicles has considerably reduced the noise generated by engines. Consequently, this has shifted the interest of researchers on reducing road noise, which is relatively less obtrusive. Currently, the process of estimating and analyzing road noise has become an important task in the early stages of vehicle development.

In general, various problems on noise, variation, and harshness (NVH) are observed in vehicles. Among these, noise is broadly classified into air-borne and structure-borne noise. Structure-borne noise has a frequency of less than 500 Hz (Fig. 1.1) and is generated by the mechanical structure of the car. To properly analyze this type of noise, accurately understanding the transfer paths of vibrations transmitted from the road surface to the vehicle is necessary [6]. The main transfer paths through which road noise is transmitted are the suspension mounts, which link the suspension and vehicle body [3–4]. Based on these mounts, the road noise generated by the input force from the road surface can be estimated through transfer path analysis (TPA) [1–2]. To apply TPA, representative load transfer paths (i.e., representative input points) must be selected. Mounting bolts that are used in suspension mounts are typically selected as the main transfer paths for analyzing road noise. For mounts with a single mounting bolt, the selection of the load transfer path is evidently not required; however, for those connected with multiple bolts, representative load transfer paths must be identified. This is necessary because the rumble frequency domain of road noise may be underestimated or overestimated similar to conventional methods depending on the bolt selected as load transfer path [5].

This work presents a representative input point selection method for mounts with multiple coupling to improve the road noise estimation accuracy of TPA. To select the representative points, virtual points are created by applying virtual point transformation (VPT) and central difference method (CDM) to TPA. For validation, the results estimated by the proposed methods are compared with those of the conventional TPA method.

1.2. TPA THEORY

(1) BACKGROUND

The dynamic characteristics of systems with complex mechanical structures, such as automobiles, airplanes, and ships, are difficult to identify. To represent the behavior of these mechanical systems, their dynamic modeling requires a detailed understanding of the vibration transfer mechanisms of systems. Furthermore, the transfer function, which is the relationship between inputs and outputs arising from the mounting points of substructures, must be well described to determine the desired dynamic characteristic values at the target point. In this respect, TPA is useful for identifying the vibration transfer mechanisms of complex mechanical systems and the interface forces that act at the actual coupling point. Moreover, the analysis varies depending on the characteristic or purpose of the experiment, as shown in Fig. 1.2. Although various methods have been proposed thus far, this work focuses on the most conventional version of classical TPA to align the research project with the requisites of industry.

(2) BASIC PRINCIPLE OF TPA

First, to analyze the vibration and noise characteristics of a mechanical system (described as automotive NVH in this study) using TPA, the entire system must be classified into two main substructures: active and passive systems. The active system is a vibration source, such as engines or road surfaces that are in contact with the tires during driving. It produces periodic or non-periodic input forces, which transmit vibrations throughout the system. The passive system has a target where the dynamic properties can be measured when the active system vibrates [7]. The active and passive systems can be set according to the location desired by the evaluator. In this study, based on the suspension mount, the active and passive systems are assumed to be from "tire to suspension" and from "mount bush to vehicle body," respectively, as shown in Fig. 1.3.

After substructuring the entire vehicle, tests are conducted to measure the data required for implementing classical TPA. To estimate road noise, the data must include interface forces near the mounting point and noise transfer functions (NTFs) that characterize the noise of the vehicle's interior due to the interface forces [8–9]. At least two tests must be conducted to derive these data. If the interface forces and NTFs are successfully identified by the tests, then the sound pressure level (SPL) of road noise can be calculated by Eq. (1.1):

$$\{p\} = [NTF]\{f\}. \tag{1.1}$$

(3) DATA ACQUISITION

In general, the interface forces $\{f\}$ acting on the mounting points are not measurable. Moreover, due to the complex structure of the interface, even the use of force sensors to measure the forces is difficult. Alternatively, it is possible to estimate the interface forces by measuring the frequency response functions (FRFs) of the passive system near the mounting points and the acceleration data $\{a\}$ while the vehicle is driven.

a. Impact tests

First, to measure the FRFs of the passive system, impact tests are conducted. The suspension module and tires must be removed from the vehicle body to measure the FRFs. To reproduce the load transmission from the active system to the passive system, the mounting bolt fastened to the suspension mount is assumed as the input point, and accelerometers are attached near the mounting point to measure the FRFs (Fig. 1.4). Impacting the mounting bolts at the point where the strut is fixed is difficult in the x and y directions; hence, impact cubes are made and impact is exerted on the sides of the cubes. For the impact test, microphones must be installed inside the vehicle to simultaneously measure the NTFs due to the interface forces, as shown in Fig. 1.5. Moreover, to facilitate the attachment of accelerometers, conducting the impact tests first is recommended.

b. Operational tests

Operational tests are subsequently conducted to gather the acceleration data, $\{a\}$, and measure the SPL of the actual road noise while the entire vehicle is driven. If the detachment of accelerometers is inevitable as a result of combining the systems, the reattachment of the accelerometers to their original positions must be ensured to the extent feasible. During the operational tests, the front wheels of the vehicle are set on the chassis dynamometer, as shown in Fig. 1.6. The driving conditions are established such that the harmonic component of road noise can be eliminated by setting the acceleration or deceleration of the driving speed constant. Furthermore, to verify data reproducibility, the operational tests are implemented at least three times.

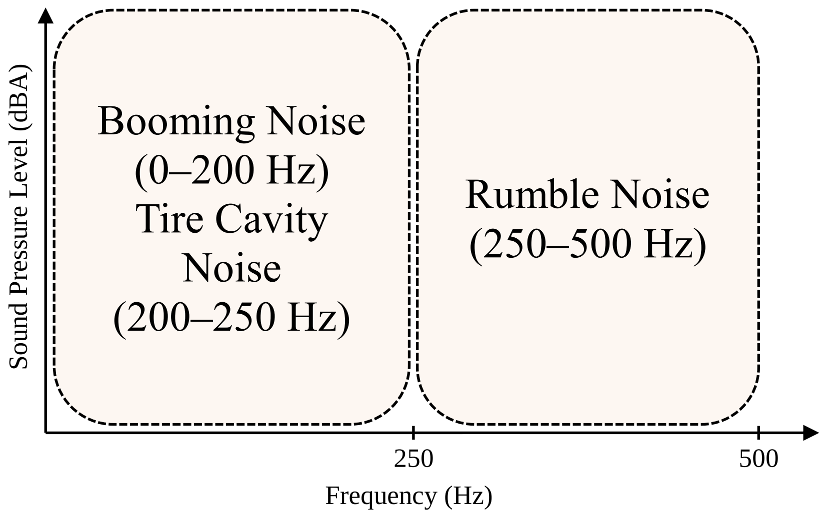


Figure 1.1 Road noise classified according to frequency band below 500 Hz.

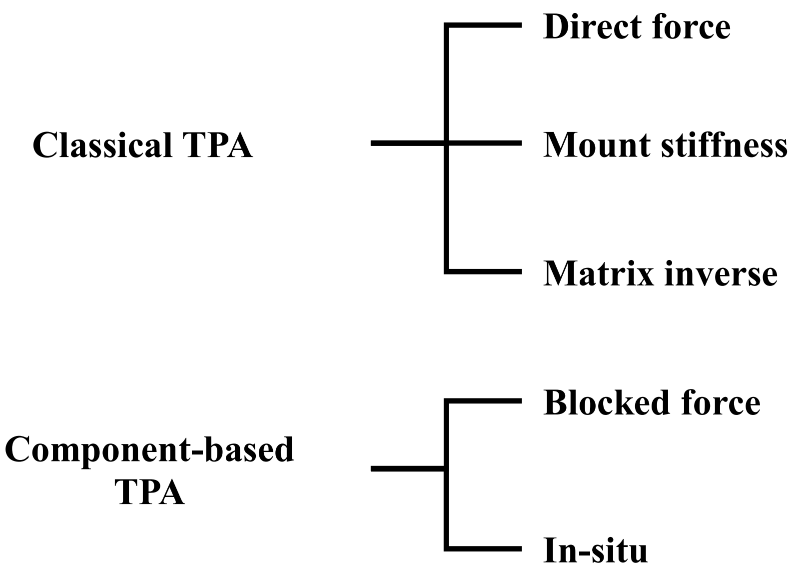


Figure 1.2 TPA methods.

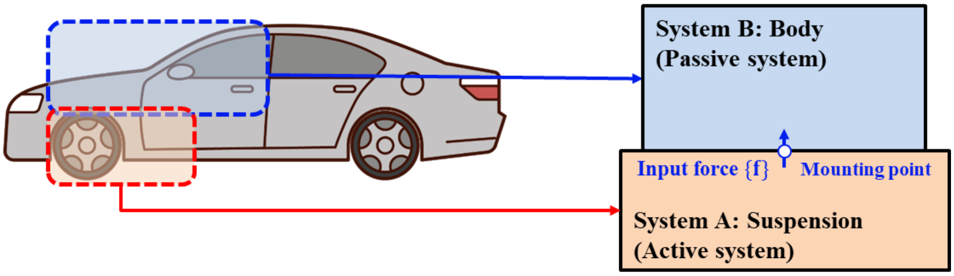


Figure 1.3 Vehicle substructuring for road noise TPA.

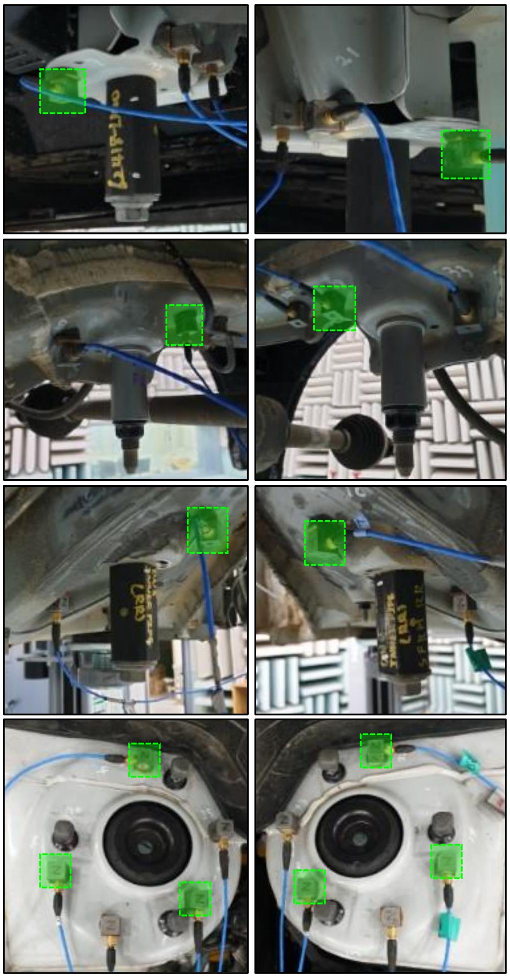


Figure 1.4 Accelerometer installation points on each suspension mount.

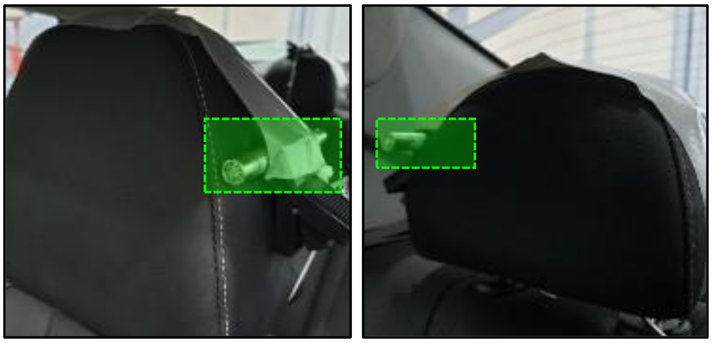


Figure 1.5 Microphone installation points.

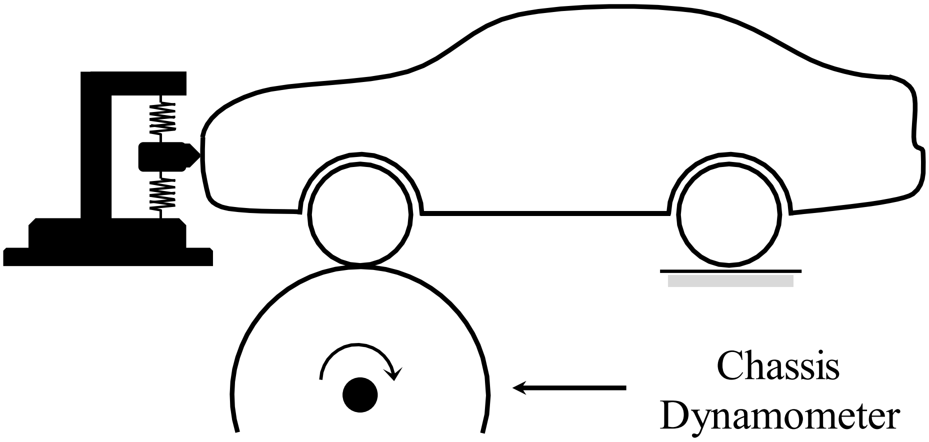


Figure 1.6 Chassis dynamometer for operational test

CHAPTER 2.
VIRTUAL POINT APPLICATION

2.1. VIRTUAL POINT TRANSFORMATION (VPT)

The VPT method is among the data post-processing techniques applied to predict the dynamic properties at coupling points particularly when directly attaching the accelerometers is difficult. In this study, the creation of virtual points in-between mounting points is implemented to compensate for the disadvantage of conventional TPA (i.e., reflecting one of the actual mounting points as an input point). To create virtual points, the accelerometers must be attached near the mounting points to obtain measurements. Then, the recorded measurements must be post-processed to fit the VPT method and estimate the data at the virtual points. As shown in Fig. 2.1, to calculate the acceleration and input data at the virtual points using Eq. (2.2), the distances from the virtual points to the accelerometers and the actual mounting points must be measured [10]. In Eq. 2.1, $[R]$ can be represented using the distance between the accelerometer and mounting points from the virtual points and converting the degrees of freedom (DOFs) of the actual measurements to fit the virtual points. Furthermore, $[W]$, which is used as a weighting matrix, is assumed to be a unit matrix, $[I]$. This minimizes the possible error, $\{\mu\}$, between real and virtual acceleration data [11]. The data obtained using VPT also include components resulting from system rotation, as given by the equations below (Eqs. (2.1) and (2.2)):

$$\{a\} = [R_a]\{q\} + \{\mu\},$$
$$\{q\} = ([R_a]^T[W][R_a])^{-1}[R_a][W]\{a\} = [T_a]\{a\}.$$

$$\{m\} = [R_f]^T\{f\},$$
$$\{f\} = [W]^T[R_f]([R_f]^T[W][R_f])^{-1}\{m\} = [T_f]^T\{m\}.$$

$$[R] = \begin{bmatrix} 1 & 0 & 0 & 0 & r_Z & -r_Y \\ 0 & 1 & 0 & -r_Z & 0 & r_X \\ 0 & 0 & 1 & r_Y & -r_X & 0 \end{bmatrix}, \qquad [W] = [I].$$

(2.1)

$$\{q\} = \begin{pmatrix} q_X \\ q_Y \\ q_Z \\ q_{\theta_X} \\ q_{\theta_Y} \\ q_{\theta_Z} \end{pmatrix}, \ \{m\} = \begin{pmatrix} m_X \\ m_Y \\ m_Z \\ m_{\theta_X} \\ m_{\theta_Y} \\ m_{\theta_Z} \end{pmatrix}.$$

(2.2)

To apply VPT to TPA, the transfer functions (i.e., FRFs and NTFs) must also be transformed according to the DOFs of the converted virtual data. These transfer functions can be transformed as given in Eq. (2.3) in a similar way to converting the actual acceleration and input force measurements into VPT data using transform matrices $[T_a]$ and $[T_f]$. In conversion, only the transfer function reflecting the converted input/output data of the virtual point can be expressed by applying the two transform matrices simultaneously. However, if the transfer functions reflect the data from the virtual and actual mounting points, then only the necessary matrix between the two transform matrices is applied to convert the DOFs of the transfer function, as shown in Fig. 2.2. In this study, the VPT technique is only applied to the struts on the upper part of the vehicle, whereas the conventional TPA is applied to the front sub-frame on the lower part:

$$[\mathrm{FRF_{VPT}}] = [\mathrm{T_a}][\mathrm{FRF_{measured}}][\mathrm{T_f}]^{\mathrm{T}},$$
$$[\mathrm{NTF_{VPT}}] = [\mathrm{NTF_{measured}}][\mathrm{T_f}]^{\mathrm{T}}. \tag{2.3}$$

2.2. CENTRAL DIFFERENCE METHOD (CDM)

The CDM uses the basic principle of the finite difference method. This technique is employed when estimating the data at the coupling points where directly attaching the accelerometers to measure the dynamic properties is difficult. By applying the CDM to the data estimation process of the virtual center point, the acceleration at the virtual point can be assumed as Eq. (2.4). If this assumed acceleration is expressed by the vibro-acoustic reciprocity, the input force at the virtual point can be expressed as Eq. (2.5) [12–13]. Similar to VPT, the CDM also requires the distance from the virtual point to the attached accelerometers and actual mounting points for data estimation, as shown in Fig. 2.3. The transformed data also include components resulting from system rotation, as follows:

$$\{a_0\} \approx \frac{1}{2}[\{a_1\} + \{a_2\}],$$

$$\{\alpha_0\} \approx \frac{1}{2\Delta_a}[\{a_2\} - \{a_1\}];$$

(2.4)

$$\frac{1}{\{f_0\}} \approx \frac{1}{2}\left[\frac{1}{\{f_1\}} + \frac{1}{\{f_2\}}\right],$$

$$\frac{1}{\{m_0\}} \approx \frac{1}{2\Delta_f}\left[\frac{1}{\{f_2\}} - \frac{1}{\{f_1\}}\right].$$

(2.5)

Transforming the FRFs in TPA to which the CDM is applied is not necessary. This is because only the NTFs of the transfer functions must be transformed after converting the input force data to fit the virtual point, as that in Eq. (2.1). The transformation of NTFs can be expressed as Eq. (2.6). Similar to VPT, the transformation matrix is only applied to certain NTF matrices that require transformation, as shown in Fig. 2.4:

$$\left[\mathrm{NTF}_{\mathrm{CDM},\, f_0}\right] = \frac{\{p\}}{\{f_0\}} \approx \frac{1}{2}\left[\frac{\{p\}}{\{f_1\}} + \frac{\{p\}}{\{f_2\}}\right],$$

$$\left[\mathrm{NTF}_{\mathrm{CDM},\, m_0}\right] = \frac{\{p\}}{\{m_0\}} \approx \frac{1}{2\Delta_f}\left[\frac{\{p\}}{\{f_2\}} - \frac{\{p\}}{\{f_1\}}\right].$$

(2.6)

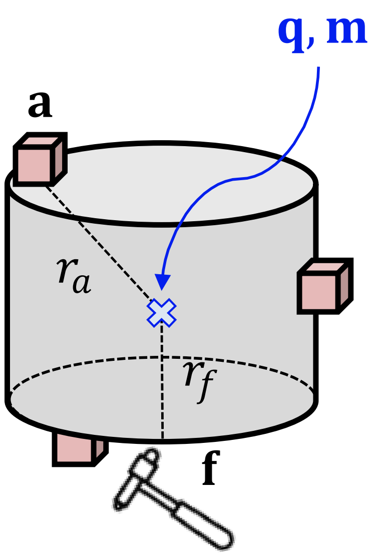


Figure 2.1 Virtual Point Transformation (VPT)

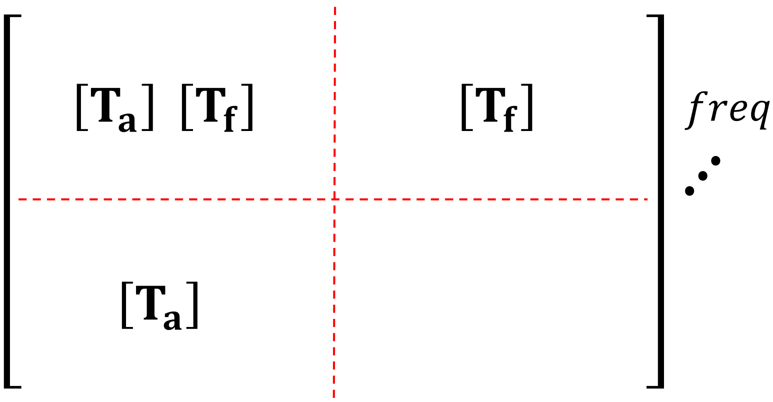


Figure 2.2 Conversion of transfer functions with application of VPT to road noise TPA

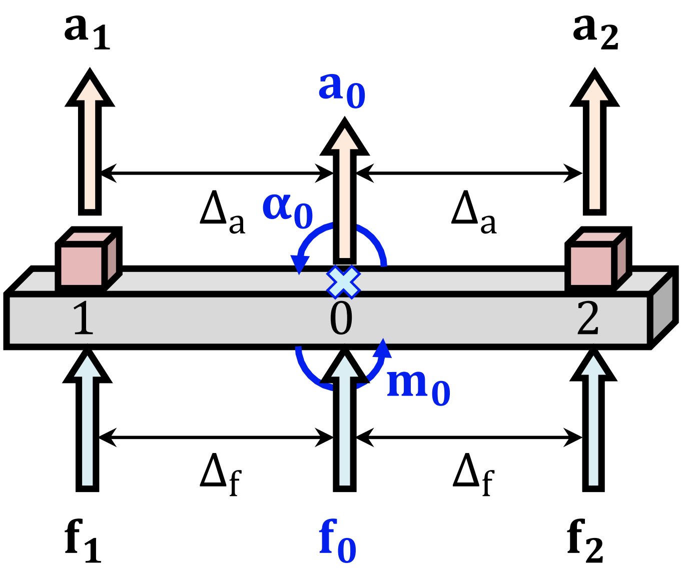


Figure 2.3 Central Difference Method (CDM)

Figure 2.4 Conversion of transfer functions with application of CDM to road noise TPA

CHAPTER 3. RESULTS

3.1. ROAD NOISE ESTIMATION RESULTS

The road noise estimation results are compared based on the test measurements. The results of reflecting each mounting bolt of the strut as a load transfer path are compared with those of the new methods applied to road noise TPA to confirm the improvement in estimation accuracy.

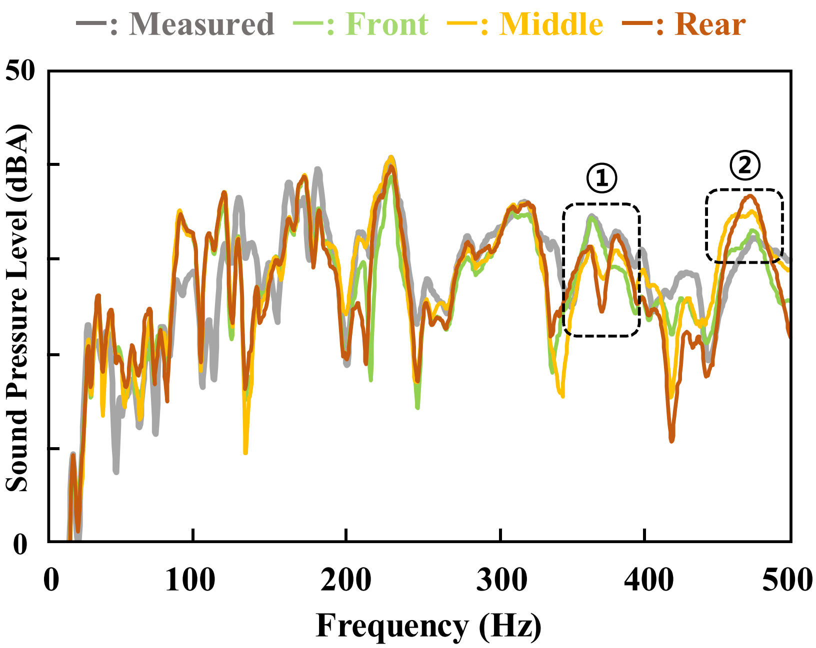
First, by applying TPA to each mounting bolt of the strut as a load transfer path, the road noise estimation results are confirmed, as shown in Fig. 3.1. Based on the graph, each road noise estimation result is similar to the actual value in the frequency bands of booming sound (less than 200 Hz) and tire cavity sound (200–250 Hz); no significant error among the estimated values is observed. However, an underestimated or overestimated domain is observed for each mounting bolt in the rumble frequency band of 250–500 Hz. Next, the results of the road noise TPA obtained by applying VPT or CDM are compared with the previous peak values in the rumble sound domain. The road noise estimation results when VPT and CDM are applied are shown in Fig. 3.2. The numerical improvement in the estimation accuracy is evident from the list in Table 3.1. The summary indicates that domains with large errors in the peak of the rumble sound band have been reduced to some extent.

3.2. METHOD COMPARISON

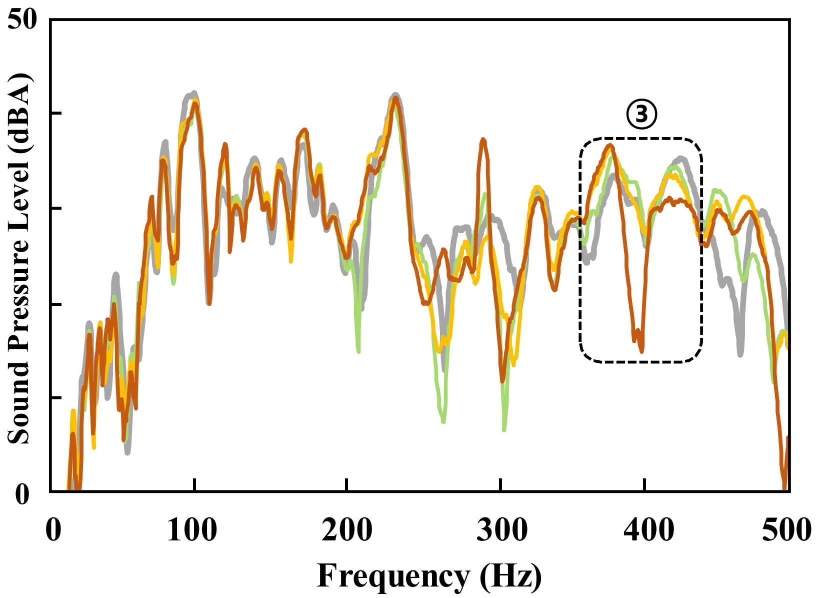
As shown in Fig. 3.3, the road noise estimation results improve in the rumble frequency band when VPT or CDM is applied to TPA. Furthermore, in the case of VPT, the estimation accuracy of TPA in the booming and tire cavity bands is similar to that of the conventional TPA method. By contrast, although the CDM has reduced the error of the rumble band peaks, its estimation accuracy in certain areas in the booming and tire cavity bands is less than that of conventional methods. Accordingly, the use of TPA with VPT at all frequency bands may be recommended for road noise estimation.

3.3. VALIDATION (ADDITIONAL EXPERIMENTS)

To further verify the improvement effect afforded by VPT and CDM, another vehicle model (test car B) is tested under conditions similar to those described above. As in the previous test, the struts are selected as multiple coupling mounts, and each mounting bolt is reflected as a load transfer path; based on these paths, the road noise estimation results are compared. First, as shown in Fig. 3.4, the estimation results for each mounting bolt indicate that the calculation accuracy of the rumble sound domain is inadequate as same as test car A. However, as shown in Fig. 3.5, when VPT is applied, the estimation accuracy of the peaks improves as indicated by the summary in Table 3.2. Different from VPT, when the virtual point is applied using the CDM, the improvement effect is less evident; hence, the latter method does not significantly differ from conventional TPA. Based on the foregoing, the virtual points of multiple coupling mounts created using the VPT method can be recommended as representative input points for road noise TPA provided that not only the booming and tire cavity frequency domains are considered but also the rumble band.

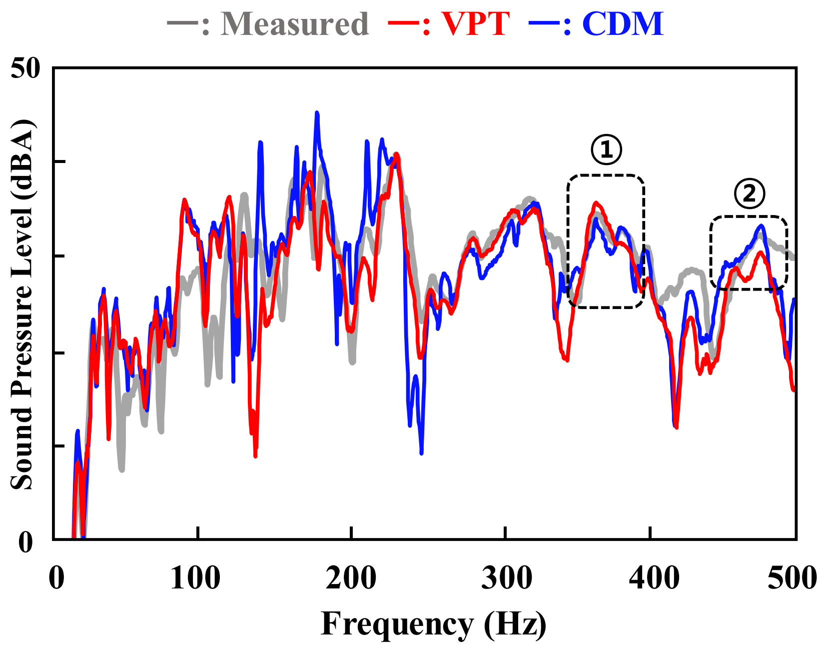


(a) Estimation results in driver's seat

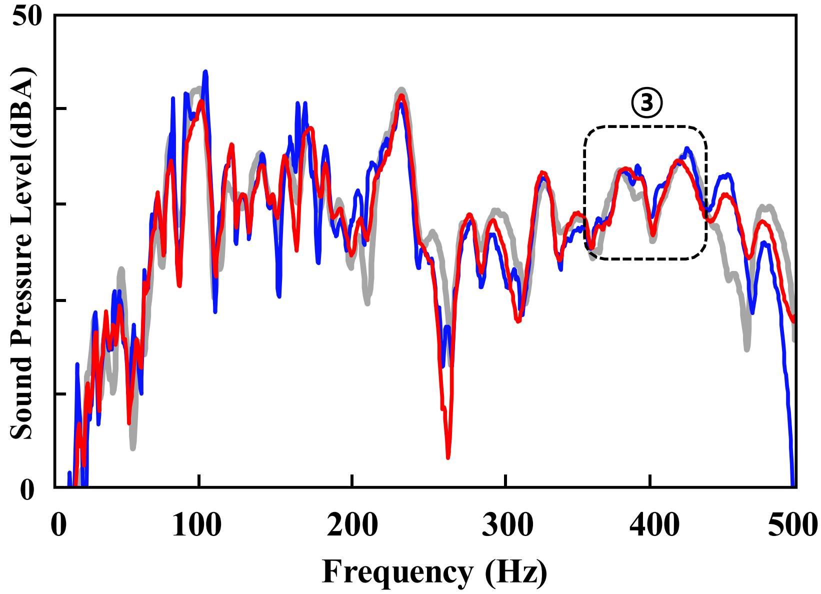


(b) Estimation results in rear seat

Figure 3.1 Road noise estimation results with each bolt selected as input point (test car A)



(a) Estimation results in driver’s seat



(b) Estimation results in rear seat

Figure 3.2 Road noise estimation results using VPT and CDM (test car A)

Car A (dBA)	Mea-sured	Frt	Mid	Rear	VPT	CDM
①	**51.40**	49.78	48.66	48.96	51.62	50.64
Error	-	1.62	2.74	2.44	0.22	0.76
②	**47.65**	49.06	51.85	52.14	46.20	48.66
Error	-	1.41	4.20	4.49	1.45	1.01
③	**54.40**	54.89	55.06	54.08	54.32	54.88
Error	-	0.49	0.66	0.32	0.08	0.48
Domain ①: 360 ~ 400 Hz Domain ②: 450 ~ 480 Hz Domain ③: 350 ~ 450 Hz						

Table 3.1 Overall dBA and error of each peak in rumble frequency domain (test car A)

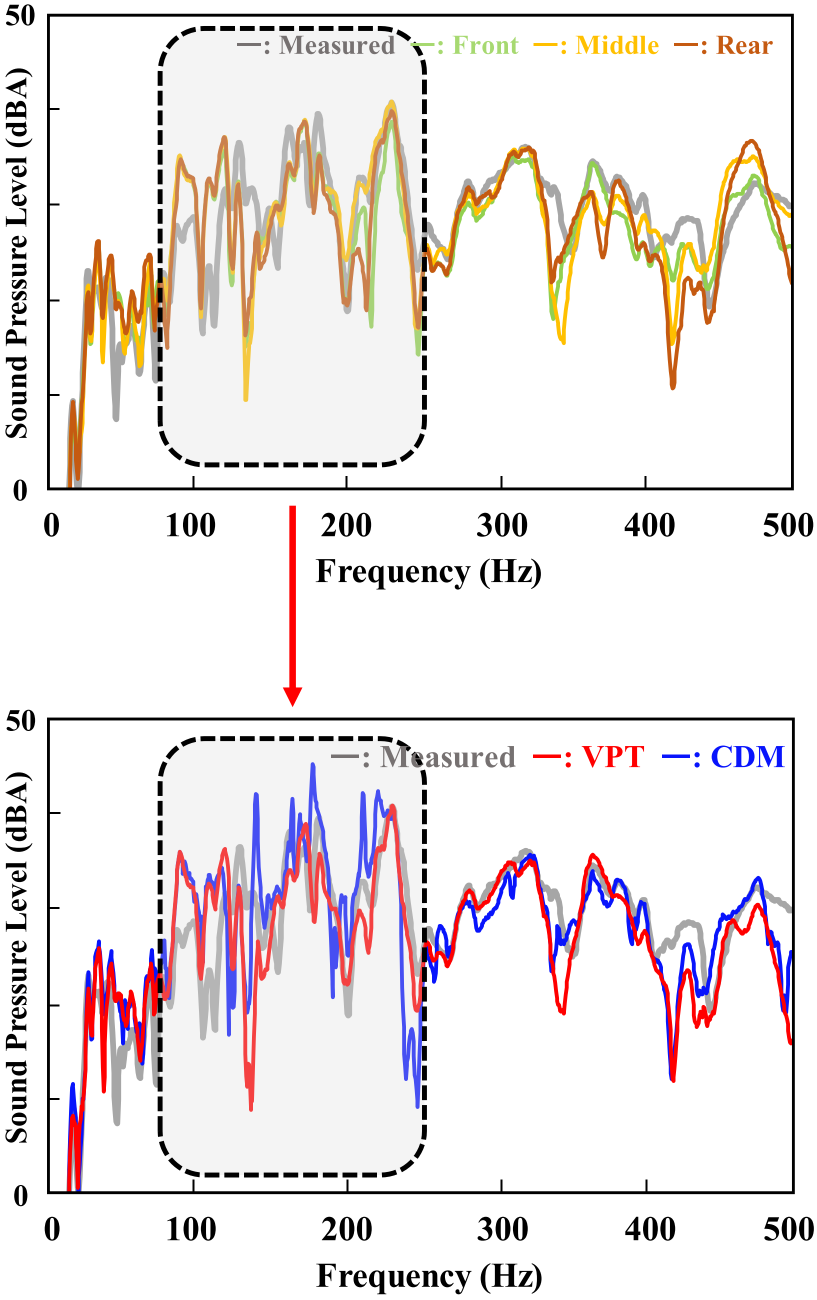
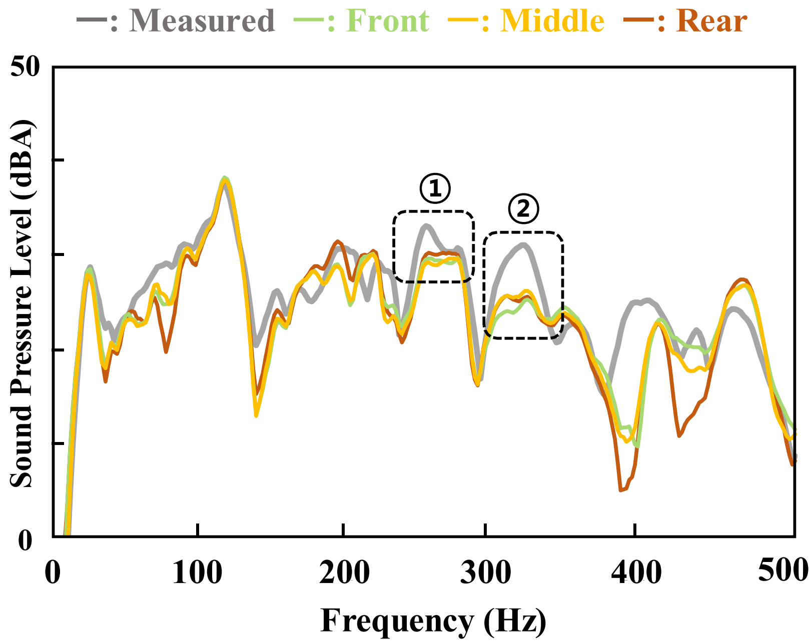
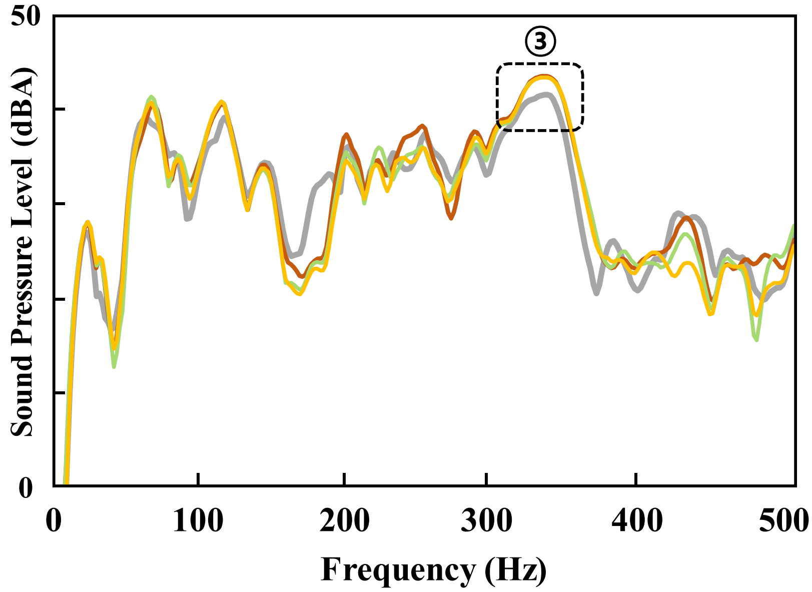


Figure 3.3 Comparison between VPT and CDM results

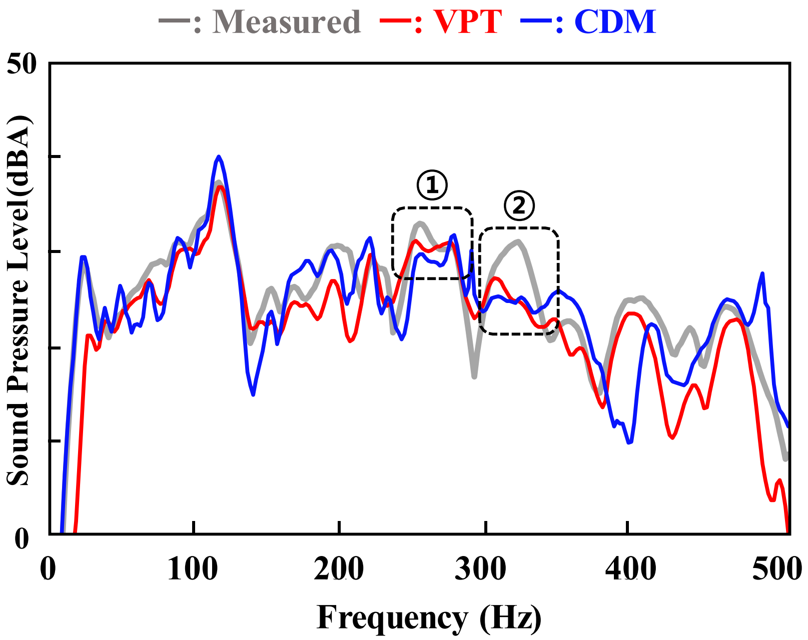


(a) Estimation results in the driver's seat

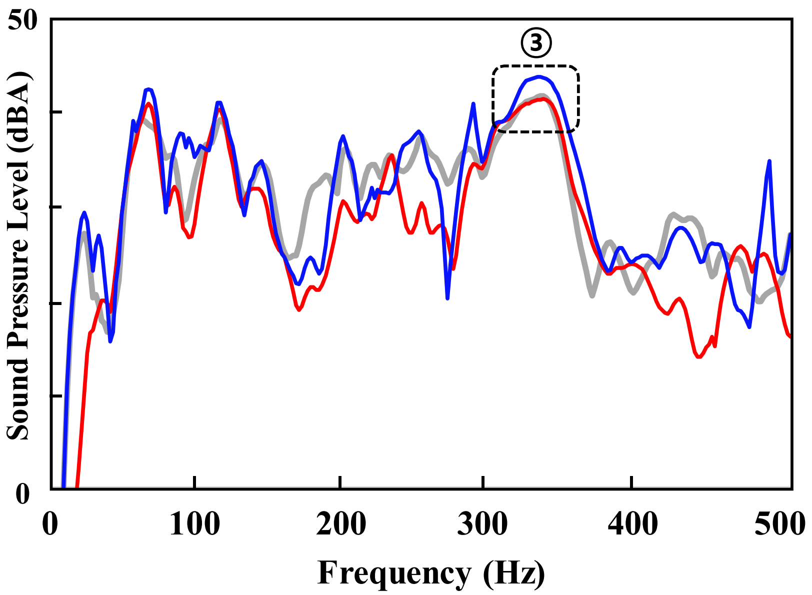


(b) Estimation results in the rear seat

Figure 3.4 Road noise estimation results with each bolt selected as input point (test car B)



(a) Estimation results in the driver’s seat



(b) Estimation results in the rear seat

Figure 3.5 Road noise estimation results using VPT and CDM (test car B)

Car A (dBA)	Mea-sured	Frt	Mid	Rear	VPT	CDM
①	**46.08**	43.86	43.57	44.34	45.14	48.70
Error	-	2.22	2.51	1.74	0.94	2.62
②	**43.85**	39.15	40.07	39.73	40.30	39.85
Error	-	4.70	3.78	4.12	3.55	4.00
③	**53.79**	55.46	55.49	55.66	53.93	55.60
Error	-	1.67	1.70	1.87	0.14	1.81
Domain ①: 250 ~ 300 Hz Domain ②: 300 ~ 350 Hz Domain ③: 300 ~ 350 Hz						

Table 3.2 Overall dBA and error of each peak in rumble frequency domain (test car B)

CHAPTER 4. CONCLUSION

4.1. CONTRIBUTION

In this work, techniques for road noise TPA are proposed to improve road noise estimation accuracy. Virtual points are created on the mounts where multiple couplings exist, and VPT and CDM are utilized as data post-processing techniques. The TPA results of the proposed methods compared with those of the conventional technique indicated that the new methods reduced the errors in the peak region of the rumble band. The CDM compared with the conventional approach was usually less accurate in estimating road noise when the frequency was less than 250 Hz. Accordingly, further tests will be carried out to verify this observation. A number of accelerometers were attached near each mounting bolt considered as a load transfer path to equally compare the measurements. For testing convenience, the number of sensors can be reduced; however, only the input data should be converted into virtual point data. The proposed methods in this work were found to be applicable not only to struts but also all vehicle mounts with multiple couplings.

4.2. FUTURE WORK

In a future study, each method will be applied to different mounting points where multiple couplings exist to ascertain whether the road noise estimation results improved. In addition, the NVH performance and road noise estimation of other vehicle systems will be analyzed by applying the proposed methods.

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국 문 초 록

최근 전세계적인 배기가스 규제로 인해 자동차 시장에서의 친환경 자동차 개발 비중이 높아지고 있다. 친환경 자동차가 개발되면서 모터와 베터리를 이용한 전장품들이 구동 시스템에 점차 적용되고 있다. 이러한 변화는 엔진으로부터 발생하는 소음보다는 노면으로부터 차량 실내로 전달되는 로드노이즈에 대한 관심으로 이어졌다. 따라서 구동 중 발생하는 로드노이즈를 정확히 예측하고 분석하는 과정은 차량의 초기 개발단계에서 중요한 업무로 자리잡고 있다.

본 연구에서는 로드노이즈 Transfer Path Analysis(TPA)의 예측정확도 향상을 위한 기법에 대해 다룬다. 로드노이즈의 주요 전달경로로는 서스펜션과 차체를 연결하는 서스펜션 마운트가 있다. 서스펜션 마운트는 단일 볼트 결합 또는 다수의 볼트가 결합되는 마운트들이 존재한다. 일반적으로 TPA를 통해 로드노이즈를 예측할 경우, 다수의 볼트가 결합되는 마운팅 지점에서 임의의 한 결합볼트를 하중 입력점으로 반영한다. 이 때, 반영되는 결합볼트에 따라 럼블음 주파수 대역인 250 ~ 500 Hz에서의 로드노이즈 재현성이 떨어지는 것을 확인할 수 있다. 이를 개선하기 위해 마운트 주위의 데이터를 이용한 가상의 포인트를 생성하여 로드노이즈 TPA에 반영한다. 본 연구에서는 Virtual Point Transfor-mation(VPT) 및 Central Difference Method(CDM)을 가상의 포인트를 생성하기 위한 데이터 후처리 기법으로 사용하며 기존의 TPA 방식과 비교해 예측결과의 개선 여부를 확인한다.