

Development and Application for Identification of Sound Source Using Inverse Method for Road Noise

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ABSTRACT

A method of analyzing the sound source identification has been studied in an attempt to enhance road noise performance. In order to reduce the cabin noise level originating in mid-frequency structure-borne noise, it is necessary to identify the sound radiating panels that contribute to the sound pressure level. The research discussed in this paper identified the sound sources using the interior cavity sound pressure levels under vehicle operational condition and the acoustic transfer functions with a loudness speaker placed on the each panel adjacent to the cavity on test bench. To prevent the accuracy of source identification from being affected by errors in measurements, the inverse matrices of acoustic transfer functions was not employed. As a result of the vehicle tests, it is verified that the method enable to predict the reconstruct cabin noise level from 100 to 600 Hz with a reliable accuracy.

1. Introduction

The enhancement of automotive interior cavity quietness is an important factor in increasing the commercial appeal of vehicles.

Simulations employing numerical computations have been recognized as an effective method of predicting interior cavity sound pressure level and applying countermeasures efficiently and accurately. In general, the finite element method (FEM) is used to analyze structure-borne noise frequencies below 200 Hz, and statistical energy analysis (SEA)⁽¹⁾ is used to analyze airborne noise frequencies above 500 Hz. On the other hand, in order to extend the range of application of simulations the frequency range to which FEM can be applied has now been expanded to above 200 Hz, and a hybrid of FEM and SEA that considers the contribution of structure-borne noise has been formularized⁽²⁾. As a result, these new methods have enabled the proposal of analytic methods that take in the mid-frequency range. However, it has been still challenging that the use of simulations by itself to study the 200-800 Hz range. Therefore, methods of analysis involving tests are generally employed for this frequency range.

Transfer path analysis⁽³⁾ is an analytic method involving tests that has been employed generally. In this method, the vibration of the panels enclosing the cabin and the acoustic transfer function between the panels and measurement points in the cabin are measured. By synthesizing these vibrations and functions, it is enable to determine the sound pressure level at the measurement point. However, the measurement of panel vibration in a real vehicle analysis entails a considerable amount of time, and the removal and reinstallation of parts can affect the repeatability of data. Therefore, there are cases in which this method cannot be employed during the actual vehicle development process. For applying and determining the specification within a limited vehicle development period, the quick identification of contributing areas is demanded. Therefore, it is necessary that the development of analytical method not relying on panel vibration measurement.

In this research, with considering the characteristics of the conventional transfer path analysis method, an analytical method focusing on structure-borne road noise, in particular in the mid-frequency range (100–600 Hz) is discussed. This method did away with the requirement for direct measurement of panel vibration by using the inverse

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matrix method to identify sound sources⁽⁴⁾. This paper will also discuss the verification of the accuracy of the method in identifying the main contributing sound sources using a real vehicle, in this case a 4-door sedan, and the achieved reduction in the cabin noise level through the use of an increased amount of sound insulator.

2. Method of Analysis

2.1. Range of Applicability of Method

In order to establish a method that could be effectively employed in the actual vehicle development process, the project target is set as the achievement of the ability to identify the sound sources that make the main contribution to cabin noise using a method of analysis that focuses on structure-borne road noise in the mid-frequency range (100–600 Hz) and the ability to predict the noise reduction level that would be achieved through the use of a sound proof package (sound insulator and asphalt sheet). In addition, the project set out to develop a method that would not require movement of the vehicle or removal of any parts for ensuring the repeatability of measurements, and that would enable the entire measurement procedure to be completed within five days.

2.2. Method Radiated Sound Sources Identification

In this section, the method of sources identification using the inverse method is discussed.

The square of the sound pressure level at any point i in the cabin, $P_i^2(\text{Pa}^2)$, is determined as the sum of the panel contributions which enclose the cabin. When each panel contribution is determined as the product of the sound power radiated by panel j , $W_j(\text{W})$, and the sound power transfer function from panel j to the cabin measurement point i , $G_{ij}(\text{Pa}^2/\text{W})$, the relation between the parameters can be expressed as Eq.(1).

$$P_i^2 = \sum_j G_{ij} \cdot W_j \quad (1)$$

The sound power radiated by the panel, W_j , is determined from the two-stage test measurements described below.

2.2.1. Measurement of cabin sound pressure level during vehicle operational condition

The cabin noise level, $\{P_i^2\}$, is measured with multiple microphones positioned inside the cabin on a chassis dynamometer under sweep condition (Fig. 1). The number of microphones used is larger than the number of panels enclosing the cabin. These noise levels are important for determining the radiated sound power from the panels using the inverse method, which is discussed later.

2.2.2. Measurement of the acoustic transfer function on a test bench

The panels enclosing the cabin are divided into smaller

areas, and the acoustic transfer function matrix $[G_{ij}]$ from each panel j to the cabin measurement points i is measured on a test bench (Fig. 2).

The layout of the microphones was the same as that of on chassis dynamometer. Loudness speaker was mounted on each panel and the noise level close to the speaker and the vibration of the speaker cone were measured simultaneously with the sound power radiated by the speaker as the reference.

Based on the results of the test measurements conducted in the two stages discussed above, Eq. (2) can be expressed as a matrix based on Eq. (1), and the sound power radiated by the sound sources can be expressed as Eq. (3).

$$\{P_i^2\} = [G_{ij}] \cdot \{W_j\} \quad (2)$$

$$\{W_j\} = [G_{ij}]^{-1} \cdot \{P_i^2\} \quad (3)$$

2.3. Reconstruction of Noise Level and Prediction of Reduction of Noise Level

Using the radiated sound power from each panel determined in Eq. (3) and the acoustic transfer functions, the square of the reconstructed noise level at any point in the cabin, P_{calc}^2 , can be expressed as Eq. (4).

$$P_{calc}^2 = \sum_j G_{ij} \cdot W_j \quad (4)$$

The radiated sound power from the panels can be reduced by modifying the structure of the vehicle framework and the panels which reduces the speed of vibration of the surfaces of the panels, and by using the sound insulating materials which increases the insertion loss (IL) performance. However, if the level of vibration



Fig. 1 Operational data under broad band excitation

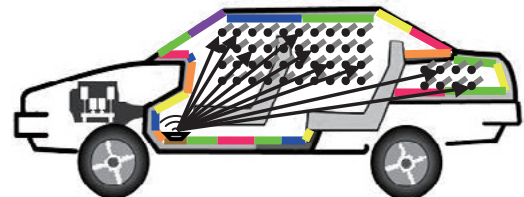


Fig. 2 Frequency response of acoustical power

of the panels is reduced by the vehicle framework and panels modification, the panel vibration has to be measured after the modification. In this method, therefore, the framework and panels modification is not be discussed. While, with regard to the use of sound insulating materials, if the properties of the sound insulation materials are known, then the IL performance following their use can be predicted without conducting measurements with the vehicle. The goal, therefore, was the establishment of the method which enables to predict the reduction of the cabin noise level that would be achieved by the employment of sound insulating materials after the sound source identification of the main contributor.

2.4. Method of Increasing Analytic Accuracy

As shown in Eq. (3), the radiated sound power from each panel is calculated using the inverse matrix of the acoustic transfer function matrix.

When the acoustic transfer function, $[G_{ij}]$, is the square matrix, the inverse matrix $[G_{ij}]^{-1}$ can be derived directly and the radiated sound power from the panel determined mathematically. However, when the noise levels at the measurement points contain errors due to the vehicle operational condition on the chassis dynamometer, the error in the determined radiated sound power from the panel can increase. The magnitude of this error is dependent on the size of the inverse matrix of the acoustic transfer function. Therefore, when measuring the multiple points in the cabin, the determination of the radiated sound power using the inverse matrices is not appropriate. It is necessary to determine the power robustly with regard to measurement errors.

For the determination, the non-negative least squares algorithm (NNLS)⁽⁷⁾ was adopted instead of the inverse matrices. The NNLS can be expressed as Eq. (5).

Since the NNLS method uses iterative computation, the calculation time increases in comparison to the inverse matrices method. However, it possesses the advantages of not being too affected by measurement errors, and of increasing the number of measurement points easily against the number of sound sources.

$$\min_{W_j} \|G_{ij} \cdot W_j - P_i^2\| ; W_j \geq 0 \quad (5)$$

In addition, by introducing the variations to the measured noise level data at each measurement point under vehicle operational condition, the error $\{p_i^2\} + \{\delta p_i^2\}$ was deliberately induced in the measured noise level, and the standard deviation for the radiated sound power from the panels is determined. Using the results of this standard deviation and the acoustic transfer functions, the variation in the reconstructed noise level is expressed as Eq. (6). Panels with a higher level of variation were judged as possessing lower reliability, therefore they were eliminated from consideration as areas for contribution analysis^{(6), (7)}.

3. Verification of Method in Real Vehicle

In this section, it is discussed that the sound source identification result using a real vehicle, which is a 2L-class 4-door sedan (North American specifications). Moreover, the reduction in the cabin noise level achieved by the use of sound proof materials is discussed.

3.1. Results of Basic Verification Using Artificial Sound Sources

For verifying the effectiveness of the developed method, the identification of the main contributing sound sources using the loudness speakers as artificial sound sources is carried out. The position of the microphones and other aspects of the test set-up were identical to those employed in vehicle tests.

Loudness speakers were positioned on the front floor (FFL), rear floor (RFR), and parcel shelf (PSL). For designing to reproduce the artificial radiated sound source from panels (Fig. 3), the speaker outputs were set as a different level of sound pressure power. The acoustic transfer functions matrix from each area to the measurement points was measured, and the radiated sound power from each area was identified. Figure 4 shows the identified radiated sound power from each area. The FFL and the PSL displayed the highest level of radiated sound power, which indicated that test results could be reproduced. By contrast, the radiated sound power of the RFR could not be distinguished from that of other areas

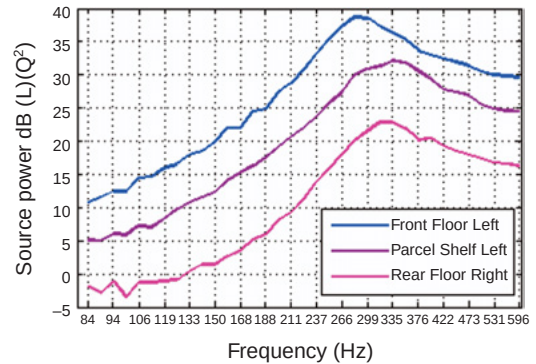


Fig. 3 Artificial excitation: actual loudspeaker power

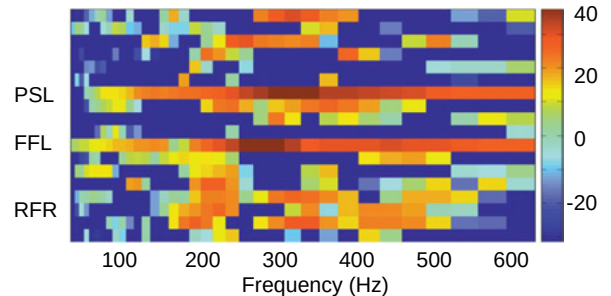


Fig. 4 Identified power radiation of each panel

not being excited by speakers. It was believed an effect of background noise during the identification of radiated power. Therefore, when the radiated power level is low, the care needs to be exercised in the analyses.

3.2. Overview of Vehicle Measurements

For cabin noise measurements during vehicle operational condition, the vehicle was placed in a semi-anechoic room. For reproducing the cabin noise and spectrum under a normal road surface driving condition, a roller bench with a roller surface reproduced on road surfaces was used. The vehicle was operated in idle and in neutral gear, and the vehicle speed was set to vary ± 6 km/h to counteract the effect of the rotation order of the chassis rollers. During verification tests, two different road surfaces (smooth and rough) and two vehicle speeds (50 km/h ± 6 km/h and 60 km/h ± 6 km/h) were employed.

Measurements of the acoustic transfer functions were conducted on the bench with the engine turned off. Because the sound power radiated from the loudness speakers (the source of excitation) was used as a reference for the acoustic transfer functions, accelerometer and microphone were mounted on the speakers (Fig. 5).

3.3. Definition of Microphones and Areas for Analysis

The microphones had to be positioned for obtaining optimum sound data from anywhere in the cabin, and the positioning had to be shared between vehicle tests and bench excitation tests. For these reasons and completing each measurement at one time, a number of microphones were selected (Fig. 6).

These rules were followed in positioning the microphones in the cabin:

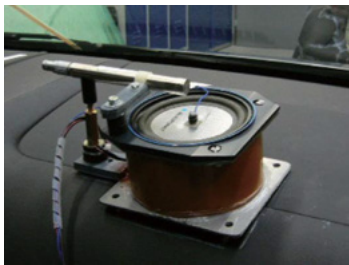


Fig. 5 Definition of loudspeaker setup

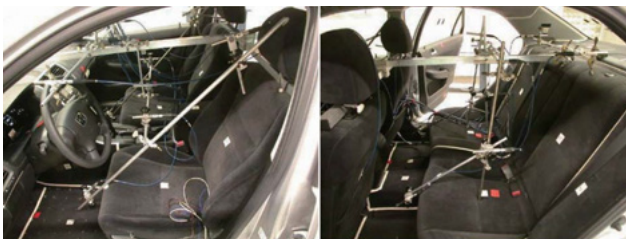


Fig. 6 Definition of microphone setup

Table 1 Definition of areas in passenger compartment for measurement

	ID	Surface
1	FDL	Front Door Left
2	FDR	Front Door Right
3	RDL	Rear Door Left
4	RDR	Rear Door Right
5	WSFL	Windscreen Front Left
6	WSFR	Windscreen Front Right
7	PSL	Parcel Shelf Left
8	PSR	Parcel Shelf Right
9	IPL	Instrument Panel Left
10	IPR	Instrument Panel Right
11	FFL	Front Floor Left (+Dash lower left)
12	FFR	Front Floor Right (+Dash lower right)
13	HLFT	Head Liner Front
14	HLRR	Head Liner Rear
15	RFL	Rear Floor Left (+Under Front Seat Left)
16	RFR	Rear Floor Right (+Under Front Seat Right)
17	RSL	Rear Seat Left
18	RSR	Rear Seat Right

- (1) To the extent possible, the microphones should be positioned at uniform intervals in the cabin.
- (2) There should be a distance of at least 30 cm between neighboring microphones.
- (3) The microphones should be positioned at least 30 cm from the nearest loudness speaker.
- (4) The microphones should be positioned at least 20 cm from the panels in the cabin.
- (5) The microphones should be positioned facing the nearest panel.

In this verification, nineteen microphones were positioned in the vehicle cabin following these rules.

The definition of the areas constituted by the panels enclosing the cabin is determined by the vehicle dimensions and the analyzed frequencies. In addition, if the areas are small, the upper limit of the analyzed frequency range becomes higher. However, by dividing the cabin up into small areas, the result will be affected from the phase relationship between the area and contiguous areas. In this method, since all values are expressed using energy, this contribution of phase would decrease the analytic accuracy. Therefore, the size of the area is maintained as large as possible. Table 1 shows the areas after division of the cabin.

By using a sufficient number of microphones to complete data measurements at one time with maintaining the accuracy of the data, the entire process, from set-up to measurement, was conducted in two days.

3.4. Results of Reconstruction of Cabin Sound Pressure

The sound power radiated by each area was identified using the sound pressure levels at the measurement points

under vehicle operation and the acoustic transfer function to each measurement point when the vehicle was on the bench. The sound pressure level at the measurement points was reconstructed using the identified radiated sound power from the panels and the acoustic transfer functions. Figures 7 and 8 show a comparison of measured and reconstructed sound pressure level measurement point at the driver's ear. Under both analytic conditions, the sound pressure level is predicted with accuracy within ± 3 dB above 100 Hz. In addition, both measured and reconstructed sound pressure levels display a peak at 237 Hz. Hereafter, an additional analysis was carried out on this frequency.

3.5. Results of Identification of Main Contributing Areas

In the identification of the contributing areas, each area contribution to the sound pressure level of any microphone at specific frequencies was determined. Figure 9 shows the results of the contribution analysis (Analyzed frequency: 237 Hz; Measurement point: Driver's seat;

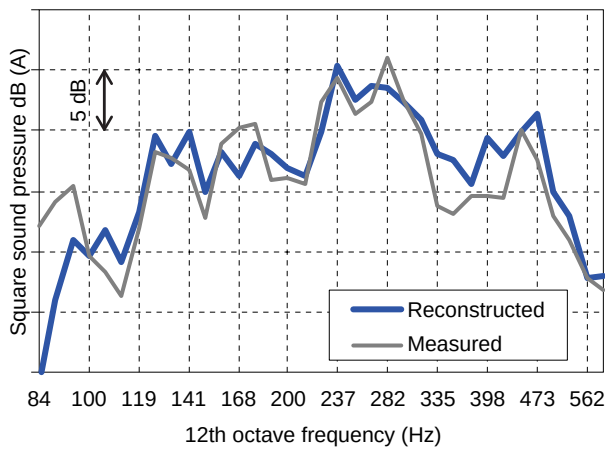


Fig. 7 Comparison of reconstruction and measurement (Rough rollers 44-56 km/h)

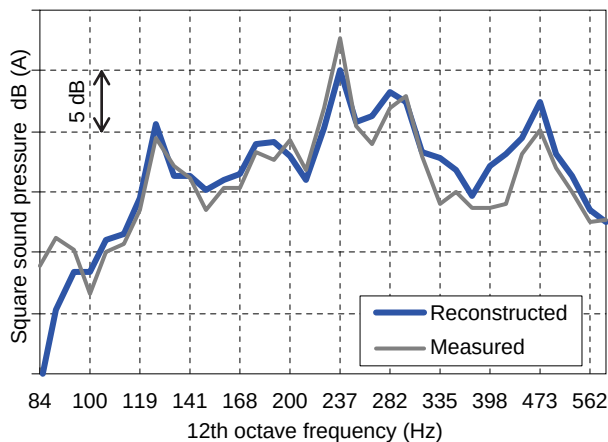


Fig. 8 Comparison of reconstruction and measurement (Smooth rollers 54-66 km/h)

Vehicle speed: 44-56 km/h). In the figure, “Recomposition” indicates the sound pressure level reconstructed from all the areas, and “Main contribution” indicates the sound pressure level reconstructed from areas contributing mainly, which levels are down to 20 dB from the “Recomposition”.

The variation in reconstructed sound pressure determined using Eq. (6) is also indicated in the each are contribution in Fig. 9. The areas indicated by hatching display a low level of variation in sound pressure, and these represent reliable analytic results. Only these areas will be employed for detailed analysis to reduce sound pressure in the cabin.

Figure 10 shows the results from Fig. 9 compiled for different vehicle speeds and different road surfaces. Under all test conditions, the parcel shelf area, both right and

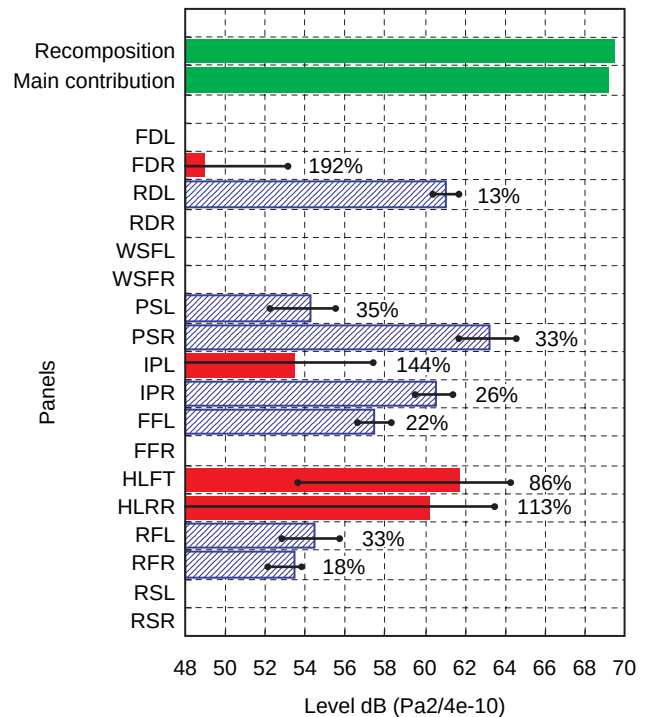


Fig. 9 Contribution of each area to sound pressure at frequency band 237 Hz

Running condition		Main contributions (Ranking)			
Roughness	Speed				
Smooth	44-56 km/h	PSR	IPL		
	54-66 km/h	PSR	IPL		
Rough	44-56 km/h	PSR	HLF	RDL	IPR
	54-66 km/h	PSL	IPR	RDL	IPL

Fig. 10 Summary of area contribution at frequency band 237 Hz

left, displayed the highest contribution at the measurement point at driver's ear. The instrument panel area also displayed a high contribution, but standard deviation was higher for different test conditions, therefore the reliability was judged as low. This area was not made the subject of countermeasures to reduce sound pressure levels.

3.6. Results of Verification of Sound Pressure Reduction Achieved by Employment of Sound Insulating Materials on Main Contributing Areas

The reduction in cabin noise achieved by employing sound insulating materials on areas that had been found as the main contribution was studied. According to the result shown in Fig. 10 indicated that the parcel shelf area made the higher contribution, sound insulating materials were employed on this area. Figure 11 shows the comparison between the results of cabin noise levels measured under vehicle operational condition and predicted cabin noise levels were compared, which

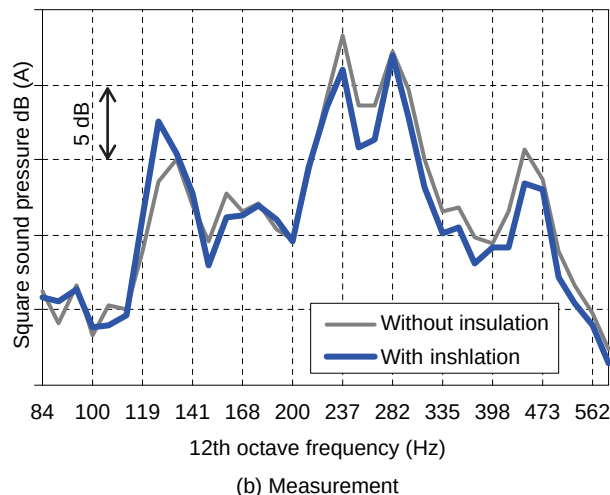
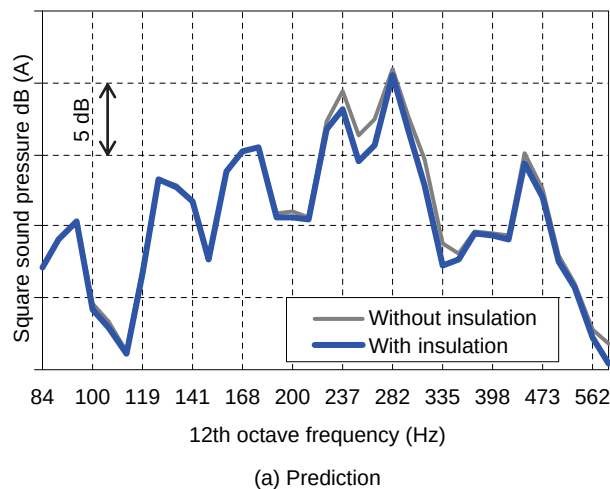


Fig. 11 Comparison of sound pressure with and without insulation (Rough rollers - 50 km/h)

condition is on the rough rollers at vehicle speeds of 44-56 km/h. The prediction results displayed a good level of accuracy, centering on 237 Hz.

3.7. Verification of Effect on Cabin Noise under Driving Condition on Road Surfaces

The effect of the countermeasures applied in this project under driving condition on a road was verified. Figure 12 shows the reduction in sound pressure at the driver's ear achieved by the employment of sound insulating materials on the parcel shelf area. The sound pressure level at 237 Hz has been reduced as well as on the chassis roller.

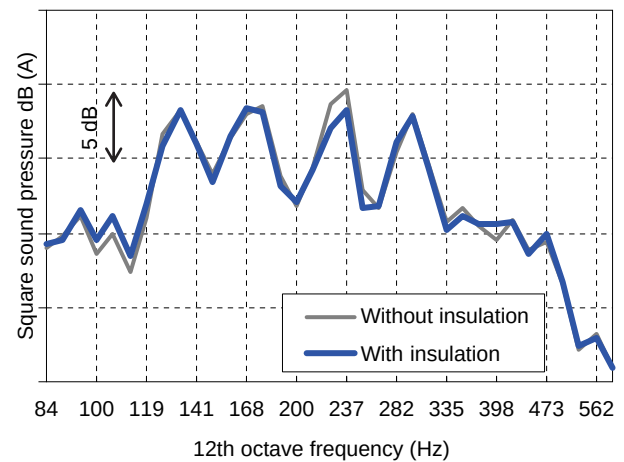


Fig. 12 Comparison of sound pressure with and without insulation (on road - 50 km/h)

4. Conclusion

Based on the transfer path analysis using the inverse matrix method, a method focusing on medium-frequency structure-borne road noise enabling identification of the main sound sources and reduction of cabin noise levels has been developed.

The use of the non-negative least squares method, which is not affected by issues of measurement accuracy, has increased the accuracy of sound source identification, and a method of area identification as sound sources using stochastic variables and standard deviation with reliable evaluation has been developed.

Tests in a real vehicle indicated that the reconstructed sound pressure level could be predicted with high accuracy within ± 3 dB against measurements. The main contributing areas can be also identified, and the effect of employment of sound insulating materials predicted.

By doing away with the requirement for panel excitation tests and minimizing the measurement set-up, the new method has enabled the procedure to be completed, from set-up to sound pressure reconstruction analysis, in two days.

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