

Method of Transfer Path Analysis for Interior Vehicle Sound Using Principal Component Regression Method

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ABSTRACT

This paper describes a time domain transfer path analysis method that can obtain transfer functions and the contributions of structure-borne and airborne sounds in a vehicle's interior. Vibration acceleration and sound pressure signals at the sound sources (reference points) and the sound pressure signal in the cabin (response point) were measured simultaneously to obtain the transfer functions when the test vehicle was driven. Principle component regression method (PCR), which can eliminate both crosstalk among transfer functions and noise in the measured data, was employed to obtain transfer functions accurately. In addition, a normalization procedure was developed to perform the PCR for combined data sets in which both vibration acceleration and sound pressure signals exist.

By applying the above methods, a highly accurate and efficient transfer path analysis method was developed that does not require a hammer test.

1. Introduction

The cause of most noise and vibration in the interior of a vehicle when driven is vibration that originates in the engine and tires, and is transmitted to the interior via multiple transfer paths. To efficiently counteract the most annoying interior noise and vibration, it is essential to identify the transfer paths that make the greatest contribution, and to modify the sources of vibration and transfer characteristics on this basis. In the last decade, transfer path analysis has been discussed as an analytical method enabling this^{(1), (2)}. Transfer path analysis consists of two steps. First, transfer functions are determined for response points for multiple input points of sound and vibration. Second, these transfer functions are combined with forces measured at the input points to generate synthesized response signals. By performing these analyses, the degree of contribution of each transfer path is obtained. Though a previous study⁽³⁾ has demonstrated the method's effectiveness, the conventional method of transfer path analysis^{(1), (2)} is unable to accurately separate the structure-borne and airborne components of vehicle interior sound.

Therefore, it is not sufficient to use the conventional method as an analysis method in order to enhance interior sound quality. In addition, the measurement of transfer functions requires a considerable number of man-hours, and there are cases in which such measurements are unable because of the time restrictions occasioned by current short development times. A simpler method of transfer analysis was therefore required.

This paper discusses the development of a new, practical method of transfer path analysis that can accurately separate structure-borne and airborne sounds, and provides an example of the application of this method to the analysis of interior sound in an accelerating vehicle.

2. New Method of Analysis

In the new method of analysis, when the sound pressure at certain points in the vehicle interior are regarded as response point signals, and the engine, tires, etc. are regarded as sound sources, acceleration vibration at points on major areas of the vehicle framework, e.g.

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the engine mounts and suspension, is considered the reference point signal for structure-borne sound. Sound pressure signals at arbitrary points in the engine chamber, and at areas around the exhaust system with large radiating surfaces, are considered reference point signals for airborne sound. Transfer functions between the response point and each reference point are determined. Vehicle interior sound is synthesized by combining these transfer functions with signals measured at the reference points when the vehicle is operating under load, to synthesize the signals for all the assumed transfer paths. After verifying that this synthesized sound reproduces the actually measured interior sound accurately enough, the contribution of each transfer path is determined. Because vector addition is applied to the signals for each transfer path, it is not possible to discuss the degree of contribution for each path in terms of simple magnitude. Since the sound source distribution is non-uniform, it is difficult to use aerodynamic noise signals as reference points on the basis of a limited number of points. Aerodynamic noise is therefore outside the scope of this method, and measurements are taken using a chassis dynamometer under conditions in which aerodynamic noise will not be generated.

2.1. Reference Point Signals for Structure-borne Sound

Using the conventional transfer path analysis method, it is necessary to excite the reference points and measure the transfer functions. However, in many cases it is difficult to ensure enough space in the engine chamber to allow excitation. In addition, while a sensor attached to the end of a hammer makes it easy to obtain force signals in an excitation test, it is difficult to measure force signals at reference points while a vehicle is being driven. The development of the new method emphasized practicality, and acceleration vibration was therefore adopted as the reference point signal, given that it requires less space for measurement and can be easily measured while the vehicle is being driven. In the transfer path analysis method discussed here, the sound pressure signal at a response point, p , is generated by multiplying the acceleration vibration signals, $\ddot{x}_i$, at n reference points (n being a number sufficient to enable reproduction of p) by their transfer function, h_i , as shown in Eq. (1).

$$p = \sum_i^n \ddot{x}_i \cdot h_i \quad (1)$$

2.2. Calculation Method of Transfer Functions using Principal Component Regression Analysis

Equation (1) cannot be used to calculate multiple transfer functions h_i from an acceleration vibration signal $\ddot{x}_i$ and a sound pressure signal p obtained from a single excitation test.

Accordingly, m ($m \geq n$) arbitrarily selected points are subjected to excitation and the sound pressure signals p_j ($j: 1, 2, 3, \dots, m$) and acceleration vibration signals $\ddot{x}_{ji}$ for each are measured to generate m linear polynomial equations, as shown in Eq. (2). Equation (2) is expressed as a matrix for convenience of calculation, as shown in Eq. (3), and the transfer function h_i is calculated.

$$\begin{cases} p_1 = \ddot{x}_{11}h_1 + \ddot{x}_{12}h_2 \cdots + \ddot{x}_{1i}h_i \cdots + \ddot{x}_{1n}h_n \\ \vdots \\ p_j = \ddot{x}_{j1}h_1 + \ddot{x}_{j2}h_2 \cdots + \ddot{x}_{ji}h_i \cdots + \ddot{x}_{jn}h_n \\ \vdots \\ p_m = \ddot{x}_{m1}h_1 + \ddot{x}_{m2}h_2 \cdots + \ddot{x}_{mi}h_i \cdots + \ddot{x}_{mn}h_n \end{cases} \quad (2)$$

$$[P] = [\ddot{X}] \cdot [H] \quad (3)$$

P_j , $\ddot{x}_{ji}$ and h_i represent Fourier spectra for their respective frequencies. Calculations are conducted in the same way for all target frequencies.

If the number of excitations, m , and the number of reference points, n , are equalized and the acceleration vibration matrix $[\ddot{X}]$ is made a square matrix, both sides of Eq. (3) can be multiplied by the inverse matrix of $[\ddot{X}]$, $[\ddot{X}]^{-1}$, to enable the transfer function matrix $[H]$ to be calculated, as shown in Eq. (4).

$$[H] = [\ddot{X}]^{-1} \cdot [P] \quad (4)$$

However, when this method is used, the accuracy of the calculation of the transfer function matrix $[H]$ declines markedly when there is noise in the measured acceleration vibration matrix $[\ddot{X}]$ and the sound pressure signal matrix $[P]$, or when there is a high degree of correlation between the acceleration vibration signals of the reference points. The principal component regression analysis⁽⁴⁾ has therefore been used in the new analytic method to provide a solution to these issues.

Using principal component regression analysis, singular value decomposition is first applied to the acceleration vibration matrix $[\ddot{X}]$ measured at each reference point (Eq. (5)), and a principal component matrix, $[T]$, is formulated using Eq. (6). This singular value decomposition completely whitens the correlations between the principal components.

$$[\ddot{X}] = [U] \cdot [S] \cdot [V]^{-1} \quad (5)$$

$$[T] = [\ddot{X}] \cdot [V] = [U] \cdot [S] \quad (6)$$

Next, the singular value matrix, $[S]$, which contains the singular values expressing the magnitude of the principal components in its diagonal elements, is focused on. Principal components that are small in comparison to the other principal components are considered as noise components and discarded. A singular value matrix from which these principal components have been discarded, $[S_r]$, and unitary matrices $[U_r]$ and $[V_r]$ are formulated, and Eq. (7) is used to reformulate a principal component matrix, $[T_r]$, from which the noise components have been removed.

$$[T_r] = [\ddot{X}] \cdot [V_r] = [U_r] \cdot [S_r] \quad (7)$$

Next, the coefficient matrix $[C]$ of $[T_r]$ for the sound pressure signal matrix $[P]$ is determined using Eq. (8).

$$\begin{aligned} [P] &= [T_r] \cdot [C] \\ [T_r]^T [P] &= [T_r]^T \cdot [T_r] \cdot [C] \\ [C] &= ([T_r]^T \cdot [T_r])^{-1} \cdot [T_r]^T [P] \end{aligned} \quad (8)$$

The above equations enable formulation of the coefficient matrix $[V_r]$, which transforms the reference point acceleration vibration signal matrix $[\ddot{X}]$ into the principal component matrix $[T_r]$ from which noise has been removed, and the coefficient matrix $[C]$, which transforms the principal component matrix $[T_r]$ into the response point pressure signal matrix $[P]$. Equation (9) can be used to calculate the transfer function h_i between the acceleration vibration signal (reference point) and the sound pressure signal (response point).

$$\begin{aligned} [H] &= [V_r] \cdot [C] \\ &= [V_r] \cdot ([T_r]^T \cdot [T_r])^{-1} \cdot [T_r]^T \cdot [P] \\ &= [V_r] \cdot [S_r]^{-1} \cdot [U_r]^T \cdot [P] \end{aligned} \quad (9)$$

It is desirable to set the number of excitations m higher than the number of reference points n ($m \gg n$) to exclude the noise component included in the reference points from the principal component analysis and the noise component included in the response points from the regression analysis.

The method discussed here can also be applied to acceleration vibration at response points originating from steering wheel vibration and floor vibration.

2.3. Verification of Transfer Functions Accuracy

Tests were conducted to verify the superiority of the method of calculating transfer functions using the principal component regression analysis, as discussed in Section 2.2.

These tests used a vehicle body that had doors and windows, but was stripped of major interior and external components, including the engine, tires, suspension and seats, as shown in Fig. 1.

As Fig. 2 shows, three-axis accelerometers were positioned at two points, at the left and right extremities of the frame, and a microphone was positioned in the cabin. The two points at which the accelerometers were located were then excited in three directions by hammers to obtain their transfer functions by the conventional method. To calculate their transfer functions using principal component regression analysis, Fourier spectra of the reference and response points during this excitation and of arbitrary excited six points were obtained. Next, two shakers were used at the two excitation points to provide up-down excitation with uncorrelated random signals, and the time domain signals of the reference and response points were obtained.

The data obtained in this way were used to find single input-single output transfer functions and transfer functions generated by principal component regression analysis. Using Finite Impulse Response (FIR) filter processing, these transfer functions were then separately combined with the acceleration vibration signals obtained from each reference point under shaker excitation to produce synthesized sounds, as shown in Fig. 3.

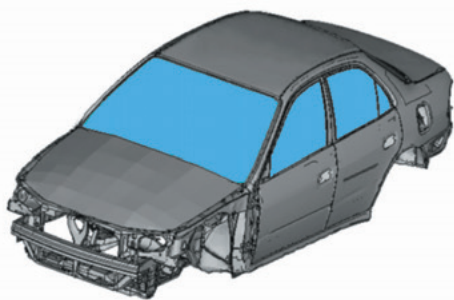


Fig. 1 Trimmed body used in experiment

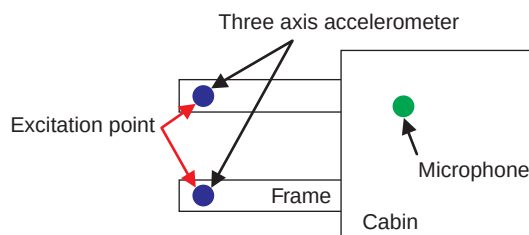


Fig. 2 Measurement and excitation points

Figure 4 shows a comparison of the power spectra of sounds measured at the response points and sounds synthesized using transfer functions obtained by the two different methods. The results show that the transfer functions obtained using the principal component regression analysis are more accurate, demonstrating the superiority of the method.

2.4. Transfer Functions of Airborne Sound

The new method of calculating transfer functions using the principal component regression analysis was next applied to airborne sound, which are thought to be inappropriate to treat as same as structure-borne sound.

As a practical method of calculating transfer functions for airborne sounds, the first proposal was to apply acoustical excitation to the structure, and treat the sound pressure signal measured at an arbitrarily positioned microphone as the reference point, i.e. as the sound source. However, as Fig. 5 shows, when the incidence characteristic of the sound wave changes, the excitation force acting

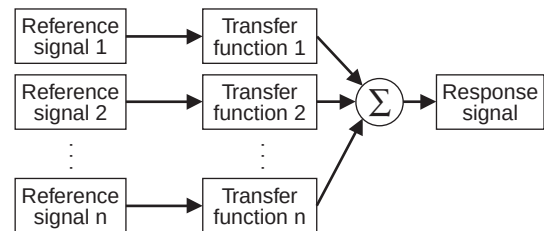
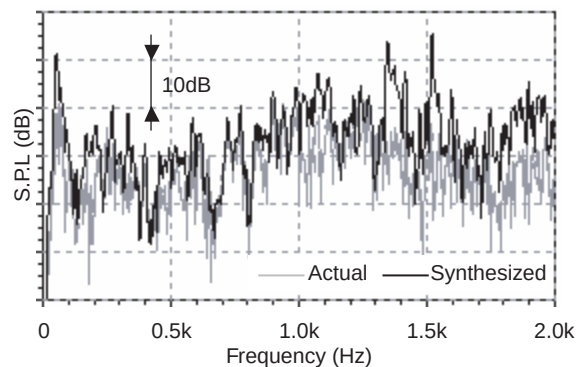
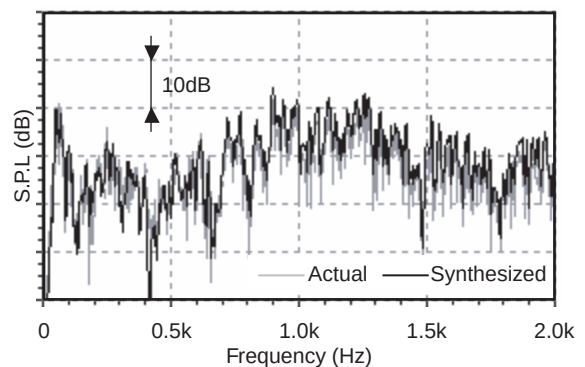


Fig. 3 Path signal synthesis with FIR filter



(a) Without principal component regression



(b) With principal component regression

Fig. 4 Comparison of actual and synthesized signals in averaged spectrum

on the structure changes, even if the sound pressure signal at the reference point is the same and true transfer functions cannot be obtained. To resolve this issue, it would be necessary to conduct excitation tests using a dummy sound source with incidence characteristics identical to the real sound source.

The method finally determined, therefore, was to calculate transfer functions using sound pressure signals measured at reference points during actual vehicle operation.

2.5. Method of Calculating Transfer Functions using Data Obtained during Vehicle Operation

When the transfer functions for airborne sound are calculated using sound pressure signals during actual vehicle operation, it is essential that there is no sound source, other than the reference point. However, this condition cannot be satisfied when a vehicle is in operation, because engine vibration and other factors are constantly generating structure-borne sound at the same time as airborne sound is being produced. Therefore, the acceleration vibration signals measured in operation were used as reference point signals for structure-borne sound, to enable transfer functions for structure-borne and airborne sounds to be simultaneously calculated. The factor that corresponds to the number of excitations m is the number of continuously calculated Fourier spectra. As time elapses, the continuously calculated Fourier spectra are arranged in the order of the columns of the reference signal and response signal matrices. Using this method, the transfer functions that reflect the effect of the engine mount and the bush characteristics affected by the driver wheel torque's reaction force under load could be obtained.

2.6. Normalization Method

To simultaneously calculate transfer functions for structure-borne and airborne sound using the response point sound pressure signal matrix $[P]$, the reference point acceleration vibration signal matrix $[\ddot{X}]$ and the reference point sound pressure signal matrix $[A]$ —all factors based on measurements conducted while the vehicle is being driven—it was considered most effective to conduct the calculations from a matrix combining $[\ddot{X}]$ and $[A]$, as shown in Eq. (10). However, the units of measurement for acceleration vibration (m/s^2) and sound pressure (N/m^2) differ, and therefore cannot be compared in terms of magnitude. That is, if noise is simply discarded from the mixed matrix $[\ddot{X}/A]$ shown as Eq. (10), it is conceivable that one of the signal components, either the acceleration vibration signal or sound pressure signal, would be discarded with the noise component.

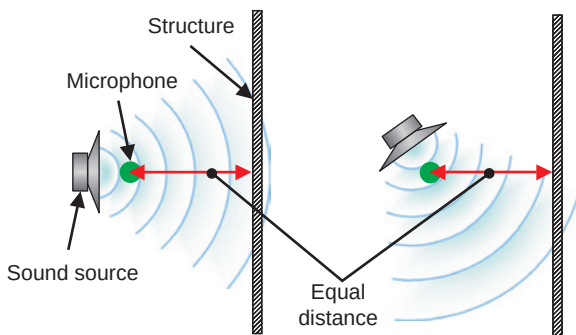


Fig. 5 Acoustic excitation power difference depending on incidence angle

$$[P] = [\ddot{X}/A] \cdot [H] \quad (10)$$

To minimize this possibility, the matrices for acceleration vibration, $[\ddot{X}]$, and sound pressure, $[A]$, are normalized before being combined.

3. Development of a Transfer Path Analysis System

Software was developed combining the ability to generate synthesized sounds and to calculate transfer functions using the principal component regression analysis method. The software also includes supplementary functions, including the ability to verify the validity of the calculated transfer functions and to produce animations of the behavior of each calculated principal component.

4. Test Verification of the New Calculation Method's Effectiveness

The effectiveness of the new calculation method was verified by applying it to the analysis of a front-wheel drive vehicle with an engine displacement of 2.4L.

4.1. Test Method

A complete vehicle was positioned on a chassis dynamometer able to absorb front wheel torque. Measurements were taken in several conditions, with the vehicle in second gear.

With respect to reference points, acceleration vibration measurements were taken in three directions at a total of 21 points, including the side of the engine at the engine mounts, the side of the body, the axle bearings and the exhaust system mounting points, and sound pressure measurements were taken at a total of 14 points including arbitrary points in the engine chamber, in the intake system and around points on exhaust system components that were considered significant contributors to the radiated sound. Two positions, the right and left ear positions of an artificial head microphone for binaural recording, were established as response points. A total of 79 channels of time domain signals were simultaneously measured, and at the same time Fourier spectra were continuously calculated as time elapsed.

4.2. Analysis Conditions

In the vehicle used in testing, front wheel torque reaction force caused the engine to tilt backwards due to acceleration loads and strike against the stopper that controlled engine mount movement, causing the spring constant of the engine mounts to change. Accordingly, the analysis was performed separately for calculating the transfer function between engine-side vibration and the body-side vibration of the engine mounts and for calculating the transfer functions between the body-side vibration of the engine mounts and the interior sound, respectively, as shown in Fig. 6.

4.3. Reproduction Accuracy of Synthesized Sound

Figure 7 shows the spectrograms of measured and synthesized sounds at the left ear of the artificial head microphone. Figure 7(a) shows the spectrogram of the measured vehicle interior sound, and Fig. 7(b) shows that of synthesized sound with acceleration vibration signals from 45 channels and sound pressure signals from 14 channels used as reference points. These results show that the

synthesized sound reproduced the measured sound with a high degree of accuracy.

4.4. Results of Separation of Structure-borne and Airborne Sound

Figure 7(b) shows a synthesis of the signals from all the transfer paths. Also, it is possible to consider each transfer path separately, or to synthesize the transfer paths within a specific delimited range. Figure 8 shows the results of classifying the sound into structure-borne and airborne components. These graphs show that the second-order level for engine speed was comparatively high for airborne

sound, as shown in Fig. 8(b), indicating that some of the transfer paths that create airborne sound contributed significantly.

Figure 9 shows a comparison of averaged spectra for structure-borne and airborne sounds within a specific range of engine speeds, showing that below approximately 500 Hz, structure-borne sound contributed greatly, while above approximately 1 kHz, airborne sound contributed greatly.

As demonstrated above, the new method is able to specify the transfer paths with high contribution from among a large number of transfer paths, and will therefore assist in determining effective countermeasures.

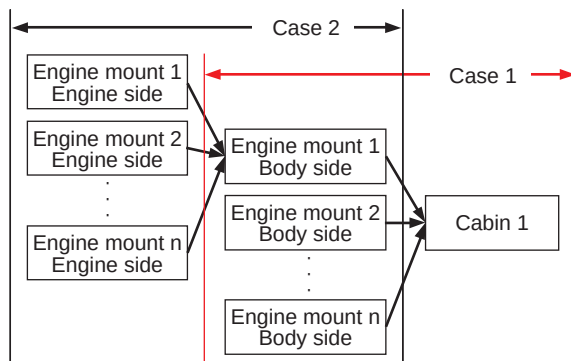
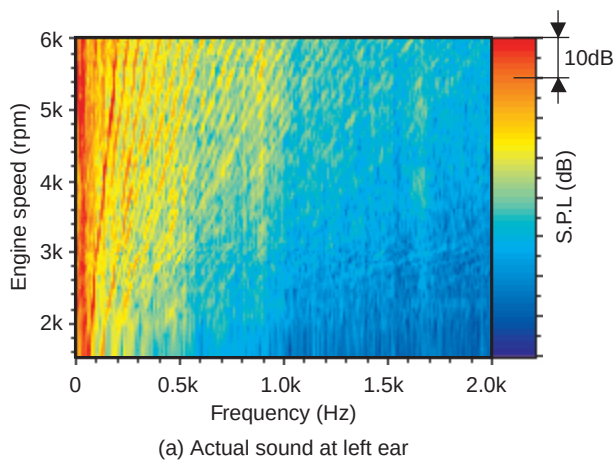
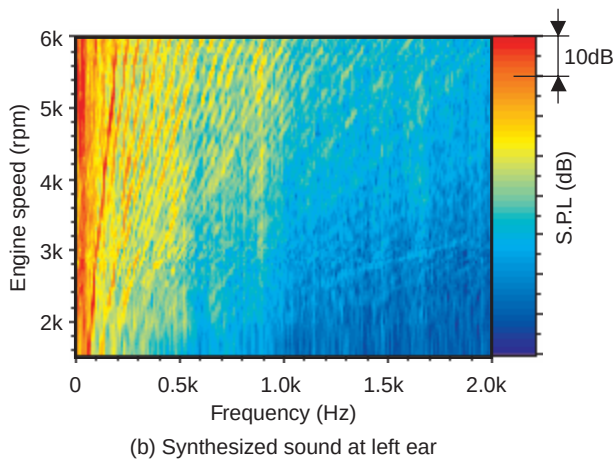


Fig. 6 Example of structural model selection

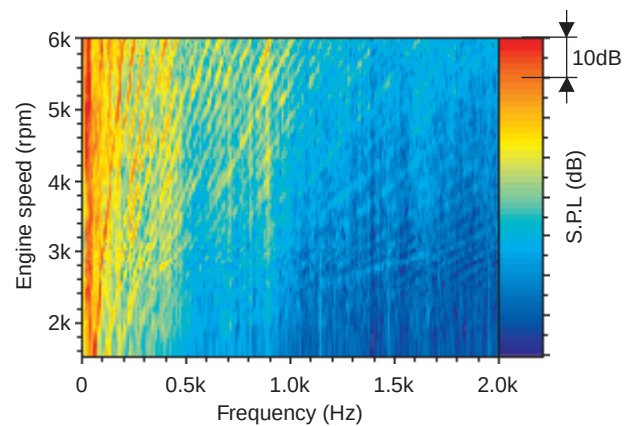


(a) Actual sound at left ear

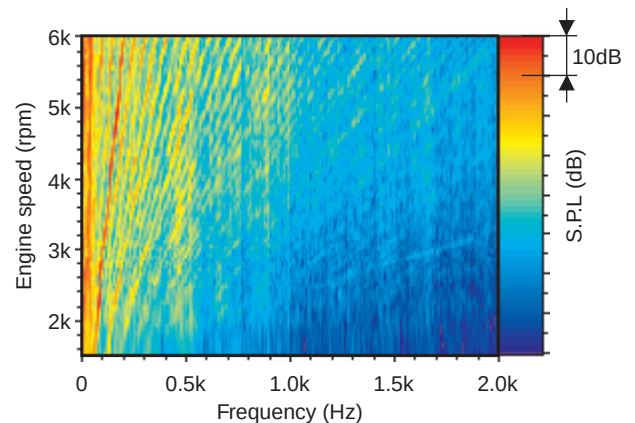


(b) Synthesized sound at left ear

Fig. 7 Comparison between actual and synthesized sounds



(a) Structure-borne sound



(b) Airborne sound

Fig. 8 Comparison between structure-borne and airborne sounds

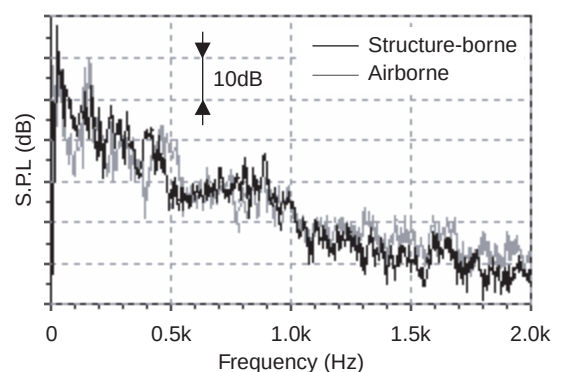


Fig. 9 Comparison between structure-borne and airborne sounds in averaged spectrum

5. Conclusion

A method of transfer path analysis has been developed that uses principal component regression and an original normalization procedure. The new method is able to separate structure-borne and airborne sounds on the basis of data recorded while a vehicle is being driven, with no requirement for an excitation test. Application of the method to an actual vehicle to verify its effectiveness indicated that it was able to identify transfer path characteristics with a high degree of accuracy, and that it was superior to the conventional method in the following respects:

- (1) The highly accurate reproduction of the synthesized sound makes the approach to modifying transfer path characteristics to enhance sound quality more clear.
- (2) There is no need to invest man-hours in performing excitation tests.
- (3) Data can be obtained using only acceleration sensors and microphones, and there are therefore few restrictions on areas to which the analysis can be applied.
- (4) Few restrictions on driving conditions are necessary.

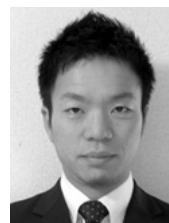
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