

Improving Suspension and Engine Mount Transfer Path Analysis Accuracy with Respect to Low Frequency Noise and Vibration

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ABSTRACT

This paper describes a transfer path analysis method used to analyze the low frequency noise and vibration contribution of suspension and engine mounts caused by second order engine vibration. This transfer path analysis method is capable of removing transmitted forces from other paths (residual forces) besides the main path at a particular degree of freedom. Compared to the conventional methods, results from this analysis method showed improved accuracy with respect to vehicle measurements. From the results of the transfer path analysis performed by using this method, frequency range and contribution by the suspension paths for low frequency noise and vibration are clarified.

1. Introduction

In the analysis of automotive noise and vibration, Transfer Path Analysis (TPA) provides a means to determine an effective countermeasure; due to the fact that the contribution, input force, and sensitivity that constitute each path, are well-defined. Because of these characteristics, TPA is used in various cases of analyses^{(1), (2)}.

However, when the systems are coupled at mutually adjacent points, as is the case with some engine and suspension mounts which are coupled to a sub-frame, multiple transfer forces affect a single connecting degree of freedom, making it difficult to separate the transfer paths. Thus, even if TPA is performed, the measurement results will not agree with the analysis results, and it will be difficult to construct a highly accurate model. Consequently, the contribution of each system for an event will not be well defined, and it will be difficult to determine system level target values in order to achieve global targets, such as interior noise and steering vibration, without excess or deficiency.

This paper describes an example of using the

conventional TPA method for low-frequency vibration and noise caused by engine combustion forces, and clarifies issues related to accuracy. Next, it describes a method (residual method) in which transfer forces (residual forces) from paths other than the main path are removed, and indicates the theoretical equations involved. It also suggests a practical judgment criterion for the connecting degree of freedom to which this method is applicable. In addition, it clarifies the advantages compared to conventional methods, and also clarifies the contribution of the suspension to low-frequency vibration and noise.

2. Description of the TPA Method

As shown in Eq. (1), the TPA method obtains the composite noise and vibration S_{All} by multiplying the input force F_i of the connecting degree of freedom of the object of analysis by the sensitivity S_i/F_i from the connecting degree of freedom to the targeted noise and vibration S_i , and then calculating the vector sum⁽³⁾. This permits an analysis of the extent to which each connecting degree of freedom contributes to the target.

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$$S_{All} = \sum_i^n F_i \times S_i / F_i \quad (1)$$

Conventional methods of obtaining transfer forces are the mount stiffness and the inverse matrix methods. The points to note when using each of these methods and the results of analysis obtained are described below.

2.1. Mount Stiffness Method

As shown in Eq. (2), the mount stiffness method derives the transfer force by multiplying mount stiffness K of the coupled mount rubber by the relative displacement $x_a - x_p$ between the input and response sides.

$$F_{MS-path} = K \cdot (x_a - x_p) \quad (2)$$

The mount stiffness method performs coupling between each input and response side by using the mount dynamic stiffness characteristics, so the contribution of each coupling becomes clear. However, in the case of a highly rigid spring-coupled path that cannot be isolated, such as the suspension, the predicted value for the transfer force does not agree with the measured vehicle result, so the accuracy is low.

2.2. Inverse Matrix Method

On the other hand, the inverse matrix method measures the frequency response $[x_{Mik}/F_{Mij}]$ and acceleration $[x_{Mik}]$ at which all of the connecting degrees of freedom are taken as the input and response, performs the inverse matrix calculation of Eq. (3), and derives the transfer force $[F_{Mij}]$.

$$\begin{bmatrix} F_{M1i} \\ \vdots \\ F_{Mij} \end{bmatrix} = \begin{bmatrix} \ddot{x}_{M1i}/F_{M1i} & \cdots & \ddot{x}_{M1i}/F_{Mij} \\ \vdots & \ddots & \vdots \\ \ddot{x}_{Mik}/F_{M1i} & \cdots & \ddot{x}_{Mik}/F_{Mij} \end{bmatrix}^{-1} \cdot \begin{bmatrix} \ddot{x}_{M1i} \\ \vdots \\ \ddot{x}_{Mik} \end{bmatrix} \quad (3)$$

The inverse matrix method enables accurate results to be obtained in a system containing a highly rigid spring coupling. However, in order to stabilize the inverse matrix calculation, it is necessary to over determine the matrix by at least twice the number of connecting degrees of freedom. Also, if multiple transfer forces affect a single connecting degree of freedom, such as in the case of the engine mount and suspension which are coupled to a sub-frame, it is not possible to extract the contribution for that path alone.

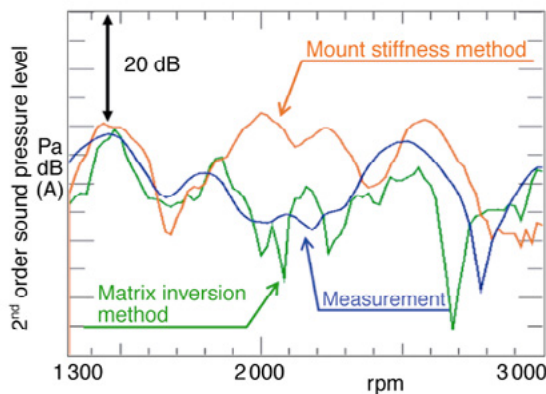


Fig. 1 Comparison of measured response with response calculated using two methods

Figure 1 shows the result of a comparison performed between the composite sound pressure derived from the above methods, and the measured value. As can be seen from the figure, the calculated result derived from the mount stiffness method is at least 10 dB higher than the result of measurement in the vicinity of 2 000 rpm. This is due to the fact that the suspension transfer force increases in this region, becoming a major contributing factor. Also, the calculated result derived from the inverse matrix method was 7 dB lower than the vehicle measurement result in the vicinity of 2 500 rpm. This is due to multiple transfer forces acting upon a single connecting degree of freedom.

2.3. Combination of the Mount Stiffness and the Inverse Matrix Methods

Analysis consisting of a combination of two methods, namely the inverse matrix and mount stiffness methods was carried out. This appears to have the merits of both methods that comprise it. The engine mount side to which the mount stiffness method is applied is isolated, and the calculation accuracy is high, however at the suspension mount to which the inverse matrix method is applied, the calculation accuracy is reduced. On the sub-frame, the suspension and engine mount are adjacent to each other. The connecting degree of freedom of the suspension is affected not only by the suspension transfer force, but also by the engine mount transfer force as well. This engine mount transfer force component constitutes a residual force, preventing an accurate transfer force calculation at the suspension coupling point. As a result, as shown in Fig. 2, the calculated value does not agree with the result obtained from vehicle measurements, so the calculation accuracy is low.

3. Description of TPA Using the Residual Method

In the conventional combined method, the matrix inversion calculation accuracy was poor due to the influence of the engine mount transfer force (residual force) upon the suspension connecting degree of freedom; therefore, the engine mount residual force will be removed by using the residual method as described below⁽⁴⁾.

As shown in Eq. (4), in order to obtain the vibration $[x_{MSm}]$ of the connecting degree of freedom at which the inverse matrix method was used, the transfer force $[F_{MSs}]$ of the

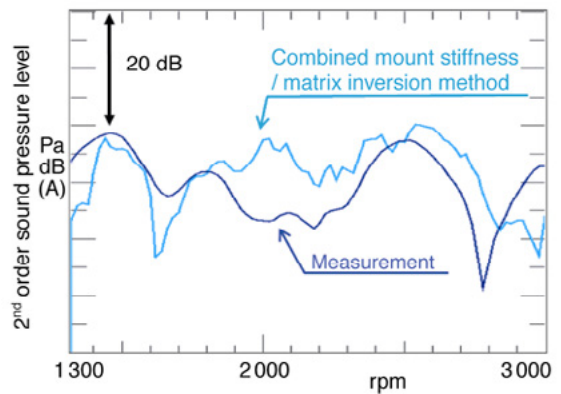


Fig. 2 Comparison of measured response with response calculated using combination of two methods

connecting degree of freedom at which the mount stiffness method was used is multiplied by the vibration sensitivity $[\ddot{x}_{MSm} / F_{MSn}]$ to the connecting degree of freedom at which the inverse matrix method was used.

$$\begin{bmatrix} \ddot{x}_{MS1} \\ \vdots \\ \ddot{x}_{MSm} \end{bmatrix} = \begin{bmatrix} \ddot{x}_{MS1}/F_{MS1} & \cdots & \ddot{x}_{MS1}/F_{MSn} \\ \vdots & \ddots & \vdots \\ \ddot{x}_{MSm}/F_{MS1} & \cdots & \ddot{x}_{MSm}/F_{MSn} \end{bmatrix} \cdot \begin{bmatrix} F_{MS1} \\ \vdots \\ F_{MSn} \end{bmatrix} \quad (4)$$

Next, as shown in Eq. (5), $[\ddot{x}_{MSm}]$ is subtracted from measured value $[\ddot{x}_{measm}]$, enabling the vibration $[\ddot{x}_{Mlm}]$ from which the influence of other connecting degrees of freedom was removed, to be obtained.

$$\begin{bmatrix} \ddot{x}_{Ml1} \\ \vdots \\ \ddot{x}_{Mlm} \end{bmatrix} = \begin{bmatrix} \ddot{x}_{meas1} \\ \vdots \\ \ddot{x}_{measm} \end{bmatrix} - \begin{bmatrix} \ddot{x}_{MS1} \\ \vdots \\ \ddot{x}_{MSm} \end{bmatrix} \quad (5)$$

As shown in Eq. (6), by performing an inverse matrix calculation on the vibration sensitivity, it is possible to obtain the transfer force $[F_{Mln}]$ from which residual forces have been removed, for that path alone.

$$\begin{bmatrix} F_{Ml1} \\ \vdots \\ F_{Mln} \end{bmatrix} = \begin{bmatrix} \ddot{x}_{Ml1}/F_{Ml1} & \cdots & \ddot{x}_{Ml1}/F_{Mln} \\ \vdots & \ddots & \vdots \\ \ddot{x}_{Mlm}/F_{Ml1} & \cdots & \ddot{x}_{Mlm}/F_{Mln} \end{bmatrix}^{-1} \cdot \begin{bmatrix} \ddot{x}_{Ml1} \\ \vdots \\ \ddot{x}_{Mlm} \end{bmatrix} \quad (6)$$

Next, the method of selecting the connecting degree of freedom at which the residual method is to be used is described below. In the coupling between the suspension, the body, and the sub-frame, the effect of the engine mount transfer force differs depending upon the coupling point. For example, the upper arm is coupled to the body, which is isolated from other connecting degrees of freedom, and the lower arm and the engine mount are coupled to the sub-frame adjacent to each other.

Figure 3 shows the measured value of the upper arm, the result obtained using the residual method, and the calculated vibration result from the lower arm transfer force alone. At the upper arm connecting degree of freedom, the upper arm is relatively unaffected by the engine mount transfer force, so the vibration generated due to residual forces is at least 20 dB lower. Also, the phase of the vibration at the suspension and body side upper arm connection is stable. Consequently, it is appropriate to use the mount stiffness method for the coupling of the upper arm.

In contrast, in Fig. 4, the lower arm is greatly affected by the engine mount transfer force, and a large difference arises between the measured vibration and the calculated vibration for the lower arm path alone. For this reason, the residual method is applied to the lower arm to remove the effect of engine mount residual forces, thus enabling the transfer force for the lower arm path alone to be obtained.

In this way, by selecting a method that is suitable for each connecting degree of freedom, it is possible to obtain a more accurate model.

Figure 5 shows a comparison of the results obtained by combining the conventional mount stiffness and inverse matrix methods, and the results obtained using the residual method. It can be seen that the results obtained using the residual method are closer to the measured results, indicating improved accuracy of this method.

4. Transfer Path Contribution Analysis Results

The results of transfer path contribution analysis using the residual method for cabin low-frequency sound pressure level caused by engine secondary vibration are described below.

It can be seen from Fig. 6 that the main contribution is from the engine mount path, and also that there is a contribution from the suspension path at 1 500, 2 400, and 2 600 rpm. Particularly, it was confirmed empirically that the contribution from the suspension at 1 500 rpm (50 Hz) is due to the mode of the damper inner shaft shown in Fig. 7.

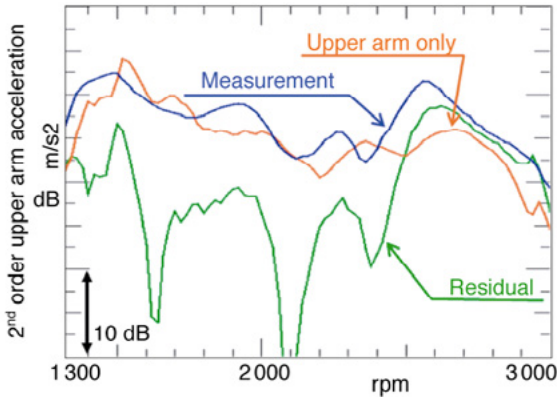


Fig. 3 Residual acceleration on upper arm

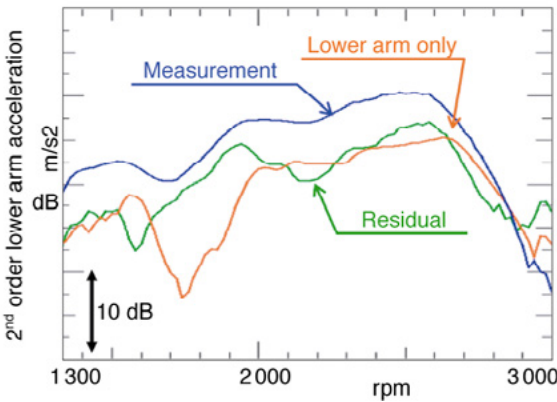


Fig. 4 Residual acceleration on lower arm

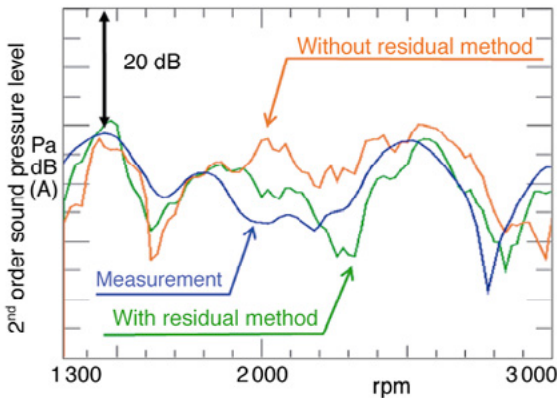


Fig. 5 Improvement of calculated response resulting from use of residual method

5. Conclusion

Transfer contribution analysis concerning a path that is affected by multiple transfer forces, such as in the case of engine and suspension mounts closely coupled to a sub-frame, was carried out, and the following results obtained.

- (1) It was found that by using the residual method, the results approximated the measured results more closely than those of conventional methods, thus indicating the analysis accuracy improved.
- (2) It was confirmed how to judge the methods to be selected for each connecting degree of freedom.
- (3) The residual method was used in the contribution analysis of the suspension and engine mounts to low-frequency vibration and noise caused by engine secondary vibration, and as a result the extent of suspension path contribution was clarified.

In the future, in order to perform low-frequency drive system vibration and noise analysis, the authors intend to create a finite element model for the suspension including the drive transfer system, and carry out a study aimed at deriving a suspension construction that halves the transfer force of low-frequency vibration and noise.

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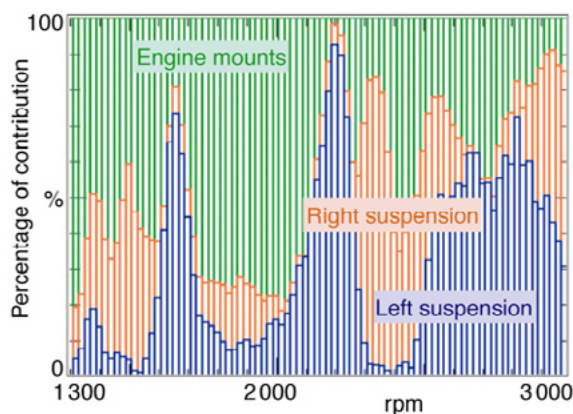


Fig. 6 Percentage path contribution of 2nd order sound pressure

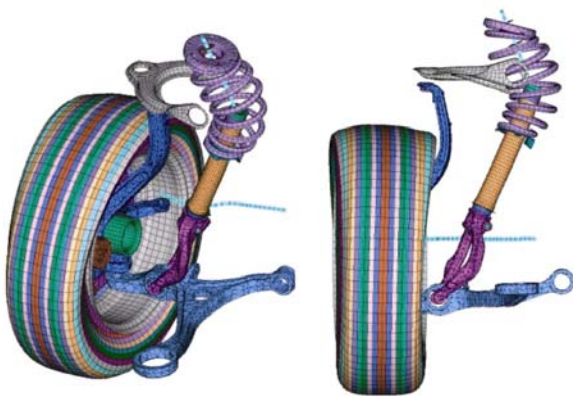
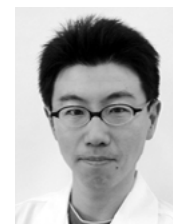


Fig. 7 Damper inner shaft mode

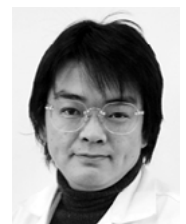
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