

Vibration Transmission Analysis of Automotive Body for Reduction of Booming Noise

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ABSTRACT

This paper presents progressive techniques based on the previous SAE papers [1], [2] for vibration transmission analysis (VTA) on finite element (FE) model using Transfer Path Analysis (TPA). The techniques are: 1) a contribution calculation technique for structure with manifold and continuous transfer paths; 2) a visualization technique of the influence degree for efficient derivation of measures for response reduction.

In VTA, influence degree of each DOF is calculated based on TPA. In order to understand characteristics of vibration transmission (VT) easily and visually by engineers, magnitude of influence degree is expressed by replacement to magnitude of displacement in the diagram of FE vibration shape. This visualization technique is applied to an automotive body structure.

The proposed techniques are applied to automotive body structure consisting of members and panels. The members are such as pillars, cross members and side members, which are the main VT paths. The panels are such as windshield and roof panel, where vibration is considered as propagating among the members. This application validates the effectiveness and usefulness of the proposed approach.

INTRODUCTION

Transfer Path Analysis (TPA) is a useful NV analysis tool in the development of automotive noise and vibration. TPA offers information and suggestion about contribution of the transfer paths and shows a dominant transfer path for taking

effective measures. TPA is familiar to engineers in case of analyzing mounting of power plants and bushing of suspensions [3]. In these applications, degrees of freedom (DOF) to analyze the transmitted forces are discrete and scalar. The number of DOF is small. There are also applications of multi-points conjunction types as that of tire and wheel [4], [5]. However, conventional TPA has seldom been applied to automotive body structure consisting of many structural members and panels as shown in [Figure 1](#). A major reason is that the vibration transmission analysis (VTA) is complicated by the many transfer paths.

One approach was proposed to analyze the complex transmission of automotive body vibration by a proper coordinate transformation of analytical DOF at the cross sections [1]. In this approach, the DOF of many adjacent nodes are treated as a cluster, so analysts easily understand vibration transmission (VT). However, this approach by only one cutting section is insufficient to detect dominant paths for taking effective measures for the body that VT paths are spread on panels. In another approach, VT path was analyzed by on many cross sections of automotive pillar [2], but this application was for a simple beam type structure, not panel.

Though TPA requires accurate estimation of transmitted forces, estimation methods as the inverse matrix method or the dynamic stiffness method [6] have a problem as accuracy dependence on the calculation condition.

In this study, element force is adopted for accurate estimation of transmitted force and is used the contribution of body structure. Visualization technique of contribution on the body structure is proposed for efficient contribution analysis. An

application is shown to be booming noise for the validation of the usefulness and effectiveness of the proposed VTA.

ANALYTICAL TECHNIQUE

TPA AND CALCULATION OF TRANSMITTED FORCE

This section describes the procedures for applying TPA to the FE model for a body-in-white. A cut section at the upper part of automotive body structure is configured on VT paths as shown in [Figure 2](#). This structure is separated into two substructures at the boundary of this cut section. Internal forces transmitting the boundary (equivalent to transmitted force) and transfer functions defined from boundary points to an output point are calculated. A response at the output point x is expressed by two factors: transmitted force vectors R and the transfer function matrix H . In the Equation, “ i ” is the number of paths, and C is the contribution of the paths.

$$\begin{aligned} \{x(\omega)\} &= \sum_{i=1}^n \left([H(\omega)]_i \cdot \{R(\omega)\}_i \right) \\ &= \sum_{i=1}^n \{C(\omega)\}_i \end{aligned} \quad (1)$$

In TPA, product of transfer function and transmitted force indicates contribution of transfer path. In another point of view, transmitted force weighted by transfer function may be regarded as an index of the VT because transmitted force plays an important role in VT. Transmitted force is usually estimated by two methods: one is the inverse matrix method, and the other is the dynamic stiffness method. For the analysis by the Finite Element Method (FEM), the dynamic stiffness method seems to be better because it is easy to utilize element force output of added spring element for the force. In this method, the stiffness of spring should be specified properly because inappropriate stiffness coefficient causes low accuracy.

It takes notice that each element adjoining the focused cutting section of body structure to be investigated plays the part of a transfer path. Calculation of contribution by element requires accurate and numerous transmitted forces in the contribution analysis. Transmitted force is obtained by the use of element force of which calculation is used the vibration response x_c , x_a of the FE model for the elements between the cut section and the adjacent section shown in [Figure 3](#) that zooms in the red circle in [Figure 2](#). The cut section “ c ” is expressed by dot-dashed lines and the adjacent section “ a ” is expressed by dashed lines. Transmitted force vectors R_c , R_a in each DOF are derived by the following equation of motion for elements.

$$\begin{Bmatrix} R_c(\omega) \\ R_a(\omega) \end{Bmatrix} = \left(-\omega^2 \begin{bmatrix} m_{cc} & m_{ca} \\ m_{ac} & m_{aa} \end{bmatrix} + \begin{bmatrix} k_{cc} & k_{ca} \\ k_{ac} & k_{aa} \end{bmatrix} \right) \begin{Bmatrix} x_c(\omega) \\ x_a(\omega) \end{Bmatrix} \quad (2)$$

where m is mass matrix, k is stiffness matrix and x is response vector of the assembly. Based on the reciprocity theorem, transfer functions defined from boundary points to an output point are derived at once by frequency response results when analysis gives a unit impulse input to a response point [7].

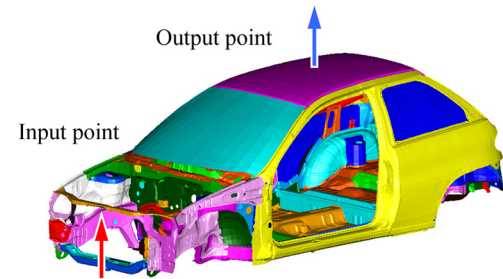


Figure 1. FE model for a body-in-white

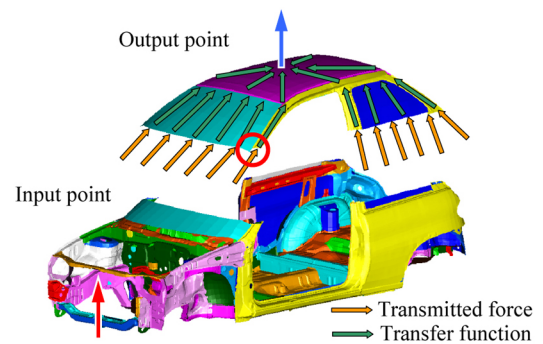


Figure 2. Overview of transfer paths

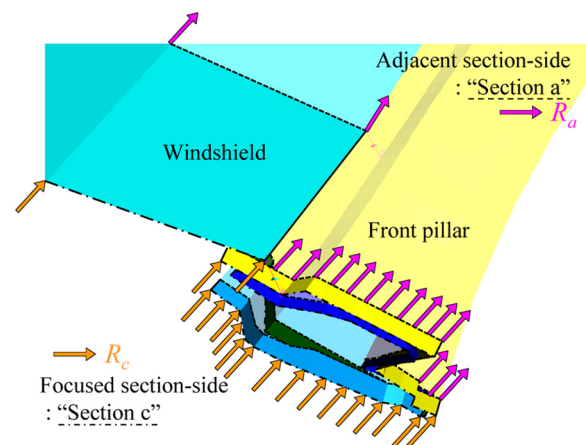
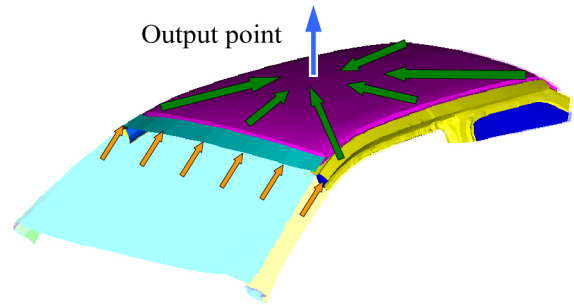
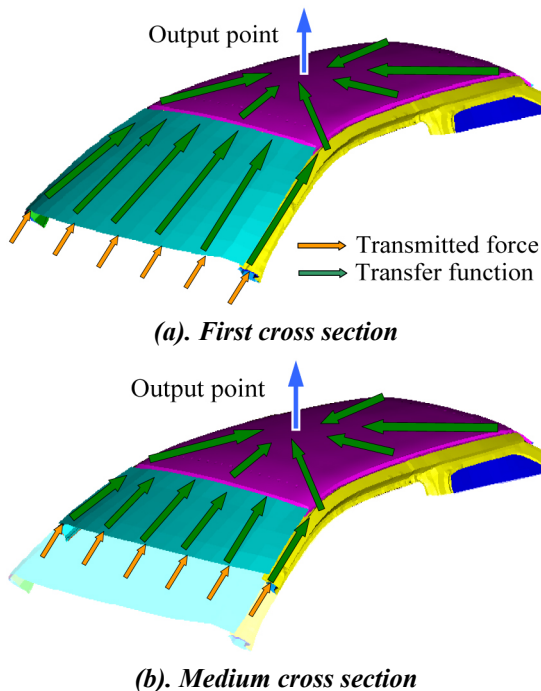


Figure 3. Focused sections and adjacent sections in VT paths at front-side body

REFINEMENT OF VT CHARACTERISTICS

In the conventional application of TPA, contribution of transfer path ranks the measures. However, in the application to automotive body structure, it is difficult to extract the suitable parts for the response reduction, because VT path varies as vibration travels through the structure. In order to break through the difficulty, we propose the contribution analysis in multiple cutting sections between input and output by using FE model.

The procedure is explained as follows. In this application, the contribution of the windshield and the front pillars is evaluated as shown in Figure 4 (a). First, contribution of this cross section is calculated, when the proposed techniques are the same as conventional TPA. Second, the section adjacent to the cross section in Figure 4 (a) is selected and is apart from it by one element. The automotive body structure is separated into two substructures at the boundary of this new section, and the contribution is calculated. This operation is repeated and the cut section rises to the roof as shown in Figure 4 (b) and 4 (c), and contributions of all cross sections in VT paths are derived.



(c). Last cross section

Figure 4. Selection of focused section

VISUALIZATION OF VT CHARACTERISTICS

Contribution analysis in TPA is not only for few and limited paths, but also for all of DOF in the cross section as a body structure. However, the structure has many nodal points on the cross section, and this requires a fair amount of time to represent and analyze the contribution of each DOF of all the nodal points. This problem is solved by displaying contributions related to three DOFs (xyz or $\theta_x, \theta_y, \theta_z$) of each nodal point on structural diagram where this contribution is described as influence degree. Contribution vector of DOF of each nodal point is orthographically projected onto the response vector. The projected parts of these contribution vectors are replaced by the response vector of corresponding DOF and are represented by the replacement to displacement in the body deformation shape. Influence degree I of each DOF is expressed by the magnitude of the contribution A and an angle θ between the response vector and the contribution vector as follows.

$$I = A \cos \theta \quad (3)$$

Focusing on one cutting section, as shown in Figure 2, we can derive only partial characteristics of VT paths. As mentioned in the previous section, cutting sections for calculating the contribution are shown continuously. The proposed approach is applied for cutting sections of all focused paths, and the VT characteristics of all paths are visualized. Considering the body deformation diagram indicated by influence degree (VT characteristic diagram), we are able to take more appropriate measures and efficient derivation of measures by the VT characteristics and spatial trends of all paths offers.