Analysis of Booming Noise using Rigid Body Information of Components

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Abstract

The FRF-based substructure analysis can predict the response of complex systems using the FRF’s of substructures. It uses the FRF’s from the finite element analysis or the experiments depending on the situation. In general, the substructure with the excitation is separated from the others by the rubber bushes to prevent the transmission of the vibration from the source to the main structure. In this case, the substructure with the excitation shows the rigid body motion up to the mid-frequency region. This paper presents a FRF-based substructure analysis by using the rigid body information of the members not using the complex finite element model of those members. The rigid body information including the mass, the moment of inertia and the coordinates of the mass center comes from the CAD data. Since the mechanism of this technique is very similar to the finite element formulation, we can apply it to the complex system with ease. Through a practical example of the interior noise in a car, the accuracy and efficiency of this approach is proven.

1. Introduction

Nowadays, it is possible to analyze the huge and complex structures with the improvements of analysis techniques. One of the efficient methods to analyze those complex structures, such as the automobiles and ships, is the substructure synthesis method. It includes the component mode synthesis method, the FRF-based substructure method. In FRF-based substructure method, the whole structure is divided into the substructures with excitation and response points. By combining the FRF’s of each substructure, we can predict the response of the whole structure. The major point of this method is that we can get the FRF’s of each substructure by the experimental or the analytical method depending on which is convenient and accurate. Many researchers have tried to predict the response in a car using the FRF-based substructure method[1-3].

In last research[4], we predicted the booming noise in a car using the FRF-based substructure analysis. During the investigation, we found that the member of the substructure with the excitation show the rigid body motion in the operation region. It is general to insert the isolation materials between the source and response to reduce the transmission of vibration energy. For example, the engine mounts made of rubber reduce the transmission of vibration energy from the engine to the body. And the rubber bush between the suspension member and the body reduces the energy flow from the road to the body. In these cases, the
stiffness of the isolation material is very small compared with those of the members, which makes the members move rigidly.

In this paper, we present a FRF-based substructure analysis by using the rigid body information of the members not using the complex finite element model of those members. The FRF’s calculated from the rigid body information and the coordinates of connecting points are assembled to predict the response of the whole structure. Since the rigid information is available from the CAD data, we can predict the response of a complex system without making the fine finite element model. As a real application, the interior noise in a car is predicted.

2. Formulation

The FRF based substructure method for complex system made of several substructures is presented. Fig.1 shows a general structure made of four substructures. Substructure A, B, C and D are connected to each other at the joint i, j, k and l as shown in the figure. The excitation at A and B will shake the whole system and we want to predict the responses at B and C. Fig.2 shows the substructure B separated from the total system. The relations to the other substructures connected to substructure B are presented as the internal forces at the joints. The definition of FRF and the superposition rule of linear system express the acceleration at the i-th point, \( a^B_i \), as follows;

\[
a^B_i = H^B_{ij} R^B_i + H^B_{ji} R^B_j + H^B_{ik} R^B_k + H^B_{ki} R^B_i + H^B_p F^B_S
\]

where, \( H^B_{ij} \) is the FRF expressing the acceleration of the i-th point excited at the j-th point and \( R^B_j \) the internal force at the j-th point, respectively. In this formulation the superscript shows the substructure where the variables are defined. The internal force is the product of the stiffness and the relative displacement between the two structures, so

\[
a^B_i = -H^B_{ii} K_i u^A_i + H^B_{ij} K_j u^A_j + H^B_{ik} K_k u^A_k - H^B_{ji} K_j u^B_j + H^B_{ki} K_k u^B_k - H^B_{ii} K_i u^C_i + H^B_{ij} K_j u^C_j - H^B_{ik} K_k u^C_k = H^B_p F^B_S
\]

where, \( K_i \) is the stiffness at the joint i and \( u_i \) is the displacement. For all the joint in the system, we can get the relations like Eq(2). Those equations show the relations between the displacements in a substructure. They are very similar to the element equations in the finite element formulation. Using the assembling technique of the finite element formulation, we can get the equations of the whole system.

\[
\{a\} + [H][K]\{u\} = \{F\}
\]

where, the matrix \([H][K]\) is the multiple of the assembled FRF matrix and the stiffness
matrix. If we use the relation of displacement and acceleration, Eq.(3) is rewritten as Eq.(4)
\[
\begin{bmatrix} H \\ K \end{bmatrix} \begin{bmatrix} \omega^2 \end{bmatrix} \begin{bmatrix} u \end{bmatrix} = \begin{bmatrix} F \end{bmatrix}
\tag{4}
\]

Eq.(4) is made of eight equations and the same number of variables. If we solve Eq.(4), we can get the displacements at each point in the system.

From the displacement at the joints, we can calculate the response at any point in the system. The response at point R in substructure B is expressed as Eq.(5) using the definition of FRF and the superposition rule of linear system as in Eq.(1).
\[
a^B_R = H^B_{R1} R^B_1 + H^B_{R2} R^B_2 + H^B_{R3} R^B_3 + H^B_{R4} R^B_4 + H^B_{RS} F^B_S
\tag{5}
\]

If there are more responses to know, we can write similar forms of equations for each response. Since the internal forces in Eq.(5) is the same with those in Eq.(1), the responses can be expressed in matrix form as Eq.(6)
\[
\begin{bmatrix} a_R \end{bmatrix} = \begin{bmatrix} H_R \end{bmatrix} \begin{bmatrix} K \end{bmatrix} \begin{bmatrix} u \end{bmatrix} + \begin{bmatrix} H_{RS} \end{bmatrix} \begin{bmatrix} F_S \end{bmatrix}
\tag{6}
\]

If we insert the displacement from Eq.(4) into Eq.(6), the response at any point can be calculated.

The matrix \([H]\) in the formulation can be delivered by the experimental or analytical approach. In this paper, the FRF’s for the substructure which shows the rigid body motion are delivered from the rigid body information of the substructures. The calculation of FRF using the rigid body information is very simple. Since the CAD programs popular in industry have the module to calculate the structural characteristics of the part, it is very easy to get the rigid body information in the design stage.

### 3. Booming Analysis in a Passenger Car

The following shows the process to analyze the interior noise in a car using the rigid FRF-based substructure method. Fig.3 is the schematic diagram of the system.

The FRF’s at each substructure must be prepared to make the matrices for the rigid FRF-based substructure method. Since the powertrain and members show the rigid body motion in the interested frequency region, which is 40~100Hz, it is better to use the rigid FRF’s. The rigid body information calculated from the CAD model and the coordinates of each joints gives the rigid FRF’s. We use the experimental techniques to get the FRF’s of the trimmed body.

![Fig.3 Rigid FRF-based Substructure Model for Booming Analysis](image)

![Fig.4 Booming Noise from Rigid FRF-based Substructure Analysis and Experiment](image)
The mechanism for the generation of noise in a cabin by the engine excitation is summarized as follows. The engine excitation vibrates the engine body. This vibration goes to the trimmed body through the center member and the cross member. The transmitted vibration shakes the body panels to generate the noise in a cabin. Based on this mechanism, designers put the engine mounts or the rubber bushes between the engine, the members and the trimmed body to reduce the energy flow from the source to the target. Since the stiffness of these isolators are so small compared with those of the members or body, the engine and members show the rigid body motion up to mid-frequency region. The modal test or analysis of the engine and the members shows that there is no elastic deformation up to 150Hz. This is a very good example for the rigid body FRF-based substructure analysis presented in this paper.

Fig. 4 shows the interior noise level predicted by the rigid FRF substructure analysis. When compared with the experimental results, the trends of the noise level are very similar. The booming at the 1800 RPM is described very well. The noise level is higher than that from the experiment by 5dB, but this is not so important problem since these tools are used in the preliminary design stage. Through this example, we can conclude the rigid FRF-based substructure analysis can be an effective tool to analyze the response of the complex real problem with the rigid body motion.

4. Conclusions

To analyze the response of complex structure with rigid body motions of parts, the rigid FRF-based substructure is presented. The results are summarized as follows.

First, the prediction of the interior noise in a car is successful. Therefore, the rigid FRF-based substructure analysis is very useful for the prediction of complex systems with rigid body motions of parts.

Second, it is common that some parts in a complex structure show the rigid body motion. The example includes the interior noise by the engine excitation and the road noise through the suspension system. For these cases, the rigid body FRF substructure analysis is very effective since it can predict the response from the rigid body information from the CAD model not from the complex finite element analysis.

Third, the structure of the substructure method presented is very similar to the finite element formulation. So, the systematic construction of the model is possible. This makes the model of the parts useful to assemble the whole system.

References