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Improvement of Vehicle NVH using a Hybrid Model of Exhaust System

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1. Introduction

This paper presents a design process for the idle vibration in a passenger vehicle. Except for global modifications of a body structure, chassis system or engine mounting system, it is difficult to find the local countermeasures that can work for the idle vibration.

In order to search the optimal condition in a design space using optimal or robust design algorithms, it is general that those approaches require lots of data in order to identify the response with respect to the design variables. Since real tests come along with lots of cost and time, a designer wants to perform virtual tests using FEA (Finite Element Analysis) or FMDA (Flexible Multibody Dynamic Analysis). On the one hand, the degraded accuracy may be caused from the virtual tests. So, the designer should decide which approach is more applicable to the problem of interest when one makes the design strategy in terms of efficiency and accuracy.

This study tries to overcome the conflicting requirements: efficient calculation and higher accuracy by applying the substructure synthesis method using a FRF (Frequency Response Function) based hybrid model. The terminology “hybrid modeling” means that the computational model is constructed from different kinds of data sources. Those sources consist of test based data and numerical model based data. The “substructure synthesis” gives that a necessary data of an assembled system can be obtained by synthesizing the data of substructures. So, “hybrid modeling using FRF based substructure synthesis method” can produce lots of benefits. By applying this approach, a global, complex and unchanged subsystem can be modeled with the measured data. And a local and variable subsystem can be made with the numerical data. As a result, a computational model of the complex vehicle system can be created with higher efficiency and accuracy. Moreover, iterative calculations for design sensitivity according to design changes can be economically performed, because only information about the modified local subsystems is necessary in the whole system.

According to the pre-defined process, the exhaust system is known as one of the critical subsystems for the idle vibration. So, in order to improve the idle performance, it is required to develop a robust countermeasure of the exhaust system and its mountings. To this end, the various types of exhaust structures and variation of mountings can be taken as the control factors, in other words, design variables. In the step of countermeasure development consisting of two phases, the first phase using a deterministic design for movement to the target is undertaken to separate the resonance frequency of exhaust system far from the critical frequency range of idle vibration. The second phase using a probabilistic design for reduction of quality deviation is performed to minimize deviation of attenuation of internal forces, which is transmitted from the exhaust system to the body structure. It is finally validated to confirm robustness of the designed countermeasures and improvement of the concerned idle vibration with a proto typed vehicle.

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2. FRF Based Hybrid Model

Three kinds of computational models are available for the virtual tests. They are the finite element model, the substructure synthesis model and the test based model. According to the previous study which covered computational efficiency and accuracy in the vehicle development stage, it is understood that the substructure synthesis method using a FRF based hybrid model can give a better performance in terms of computation. So, this study will overcome the computational requirements by applying the FRF based hybrid method.

A schematic illustration of a substructure synthesis which consists of substructures A and B is depicted in Figure 1(a). As the practical example, a vehicle may be classified into the exhaust system as the substructure A and the remaining parts as the substructure B. One joint connects the exhaust system and engine. Four rubber bushings connect the exhaust system and the body structure. Figure 1(b) shows the computational model: FRF based hybrid model.

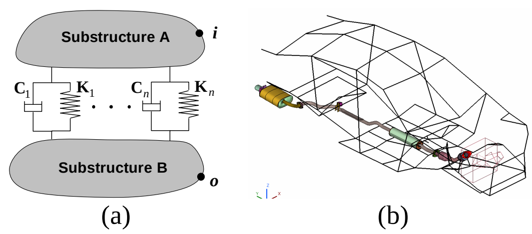


Figure 1. Substructure synthesis model: (a) Schematic illustration of a substructure synthesis and (b) Substructure synthesis method using a FRF based hybrid model

If there is no acoustic excitation in a vehicle, vibration level at a point r in the vehicle, $\mathbf{v}(r)$ created by a structural load $\mathbf{f}_s$ is

$$\mathbf{v}(r) = \mathbf{H}_{vf}\ \mathbf{f}_s \qquad (1)$$

where $\mathbf{H}_{vf}$ is the vibration transfer function from the excited DOF (Degree of Freedom) to the response DOF. This one can be synthesized as described in the Figure 2, where the transfer functions $\mathbf{H}^B_{oc}$ and $\mathbf{H}^B_{cc}$ of the vehicle are measured without the exhaust system. The transfer functions $\mathbf{H}^A_{ci}$ and $\mathbf{H}^A_{cc}$ of the exhaust system are calculated by using the correlated FEM (Finite Element Model), and the compliances $\mathbf{H}^C$ of the mounting bushings and connectors are obtained by using both measurement and calculation using FEM.

$$\mathbf{H}_{vf} = \mathbf{H}^B_{oc}[\mathbf{H}^A_{cc} + \mathbf{H}^B_{cc} + \mathbf{H}^C]^{-1}\mathbf{H}^A_{ci}$$

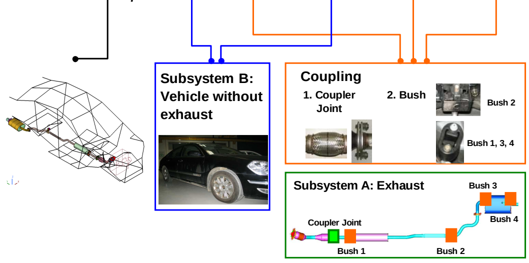


Figure 2. Computational model using FRF based hybrid model

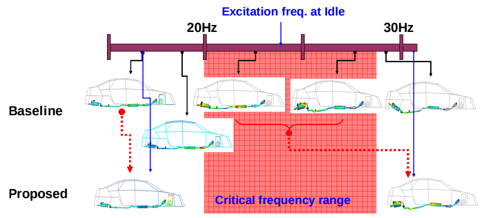
3. Design of Exhaust System

Reviewing the modal map for the idle vibration, the structural modes of exhaust system were located near the idle frequency, 20Hz ~ 30Hz. Through a few validations, it was obvious that the exhaust system was a major cause for the idle vibration and the structural mode at about 24 Hz is critical. So the design target was set to move the exhaust mode without any side effects.

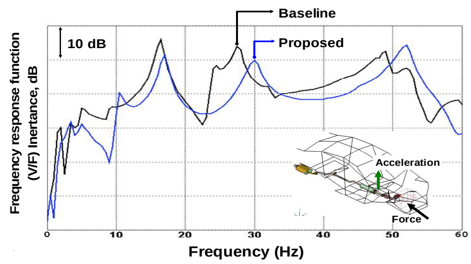
The exhaust system consists of a structural member, a joint and a few mounting bushes. The structural member includes a pipe and mufflers. A joint connects the exhaust system to the engine and the mounting bushes couple the exhaust system and the body structure. It was difficult to develop the exhaust system for NVH performances: structure-borne noise and air-borne noise because there were lots of quality deviations resulting from the dynamic characteristics of the joint and mounting bushings. In order to conquer complexities of a robust development of countermeasures, it is more efficient to divide a big step into two small phases: 1) deterministic approach for movement to the target and 2) stochastic search for adjustment of quality deviation.

At the first phase, a deterministic design was carried out to achieve the deterministic target. Taguchi method was applied at this phase. At the second phase, a probabilistic design will executed to minimize the quality deviation of a response. Reliability Based Deign Optimization can be applied for this stochastic search. Meanwhile, it is general that a robust design requires lots of iterative computations and higher accuracy. This study tried to overcome these conflicting requirements by applying the substructure synthesis method using a FRF based hybrid model.

Pre-validation of the proposed design was performed by using the hybrid model. Figure 3 compares the structural modes and the critical VTF expressed in Equation 1. The frequencies of the critical structural modes were moved from inside to outside of the critical frequency range and the magnitude of VTF was decreased.



(a) Structural modes



(b) Vibration transfer function

Figure 3. Comparison of mode separation and VTF (Vibration Transfer Function) between baseline and proposed design

It is graphed in Figure 4 that the vibration level at the driver seat under the idle condition was reduced by more than 5 dB. This data was obtained after validation of the proposed design on a test vehicle.

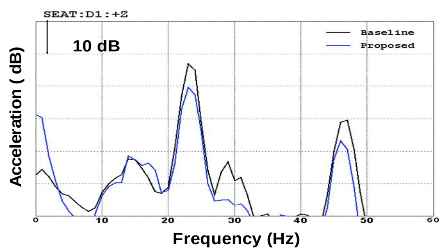


Figure 4. Comparison of idle vibration level between baseline and proposed design

4. Conclusion

In this study, a robust design process of the exhaust system has been introduced for the idle quality improvement. The substructure synthesis method using the FRF based hybrid model has been adopted for iterative calculations. As a result of the design, it has been predicted that the frequency of concerned modes are shifted to the target frequency range and the magnitude of VTF peak is decreased. Finally, it has been validated that the concerned idle vibration is reduced by more than 5 dB.