

Method for Predicting Vibration Transmission of Car Air-conditioning Hose in Light of Prototype-less Development

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ABSTRACT

A method for predicting the transmission of vibration by air-conditioning hose was devised for the purpose of examining the reduction of booming noise in the cabin and of engine noise caused by engine vibration during acceleration. For the stand-alone model of the hose, a multi-layered structure was recreated to take into account the anisotropy of the reinforcing layer. With regard to the internal pressure exerted by coolant gas sealed inside, influence factors that do not contribute to analytical precision were omitted, thereby shortening the time taken by analysis. A model of the vehicle state was created by joining a modal model of the body by the mode synthesis method, and vibration transfer function from the engine to the body was calculated. Calculation successfully yielded results with an error of 2% in the frequency and an error of 3 dB in the transfer function level. In addition, measures devised for the modeling method and calculation conditions enabled the total analysis time to be kept within 24 hours. With this prototype-less approach, the vibration transfer in air-conditioning hose can now be predicted.

1. Introduction

The demand for quietness in automobiles is increasing, and the reduction of booming noise composed of the main order components of engine vibration and engine noise composed of the high order components is an important issue⁽¹⁾ that largely determines the customers' impressions of a vehicle. At the frequency range of approximately 100 Hz to 1000 Hz where solid transfer of engine vibration is the main factor, there is a variety of transfer paths. One of these is the path shown in Fig. 1, whereby the engine vibration is transmitted from the air-conditioning hose (hereafter, the hose) and becomes cabin interior noise.

When the cause of engine noise and booming noise in the cabin interior was determined to be transmission by the hose at the stage when a prototype vehicle had been created, it would often be the case that the layout of parts in the engine compartment was already fixed. Consequently, making major changes to the hose routing could be a challenge, and taking noise countermeasures against hose transmission had to impose additional cost and mass.

Recently there has been a shift toward development with fewer returns so as to shorten the development schedule and reduce development cost. Therefore there is greater need for

a prototype-less development process that uses model-based systems engineering (MBSE). However, although there has been some research⁽²⁾ on vibration transmitted through the hose, there is no simulation technique for predicting the vibration transfer function (hereafter the transfer function) from the engine to the body. The reasons for that include the hose, which is made from multiple layers

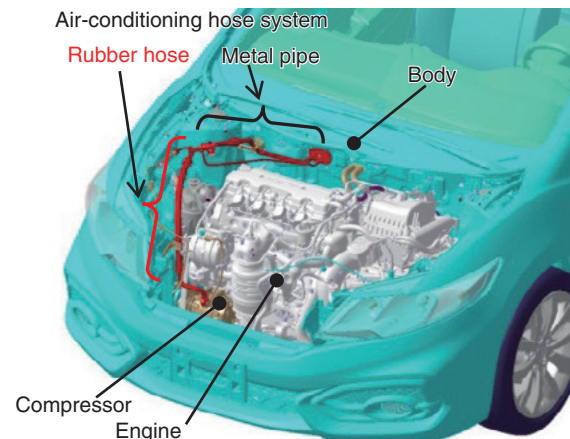


Fig. 1 Car air-conditioning hose system

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of different material, as shown in Fig. 2, the modeling of the influence of internal pressure from the coolant gas, the increased calculation time, and other such technical issues. The present research, therefore, has been oriented toward resolution of these various technical issues and so realization of simulation of the vibration transfer function of the hose in its installed state in a vehicle, with a view to prototype-less development using MBSE.

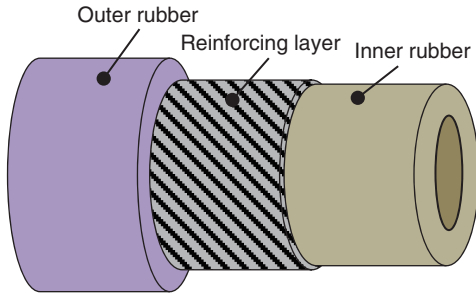


Fig. 2 Structure of air-conditioning hose

2. Development Goals

The goal of the present research has been to create a technique for predicting the transfer function of the hose in order to support prototype-less development.

It is conceivable that calculating precision can be heightened by more faithful modeling of the actual object. However, making the model more detailed than necessary leads directly to increases in modeling time and calculation time. The technique in this paper is intended for application to product development, and it is therefore required to achieve a balance between the two contradictory requirements of higher prediction precision and shorter analysis time.

First, a target for the minimum necessary transfer function prediction precision was set. As shown in Fig. 1, the hose is connected to the air-conditioning compressor. The compressor resonance frequency is generally from 100 Hz to 1000 Hz. Since this is close to the hose resonance frequency, it is necessary to examine the variance in the hose and compressor resonance frequencies. For that purpose, it was reasoned that prediction of the hose resonance frequency required precision of about $\pm 5\%$. In addition, in order to enable examination of specifications during development without obstructing the process, it is necessary to calculate the peak levels of the transfer function with a precision of ± 3 dB. Consequently, the target prediction precision was defined as a frequency error of $\pm 5\%$ for the vehicle state transfer function and ± 3 dB for the transfer function level.

The total time taken by analysis, including modeling time and calculation time, was also considered. On the assumption that the work time in a single day is eight hours,

then it was reasoned that design work could proceed without obstructing the development schedule if results could be obtained within three days from the start of analysis. A total time of 24 hours or less was set as the target.

3. Overview of the Created Technique

As shown in Fig. 3, the air-conditioning hose layout has two systems, the high-pressure pipe and the low-pressure hose. The low-pressure hose generally links the engine and the body, so structurally it is likely to transmit vibration. The low-pressure hose connects the air-conditioning compressor that is mounted on the engine with the evaporator that is attached to the body, and most of it is made up of metal pipe. In the middle between them, however, a rubber hose is ordinarily used in order to cut off the vibration. The object of the technique developed here is the low-pressure hose that, for the above reasons, is considered important in the transmission of vibration.

The applicable vehicle was defined as a medium-size sedan model. The state of the hose when predicting the transfer function fully reproduced the actual state as shown in Fig. 4.

The coolant gas that flows through the low-pressure air-conditioning hose in its installed state in a vehicle is at a pressure of approximately 1 MPa. In order to handle that

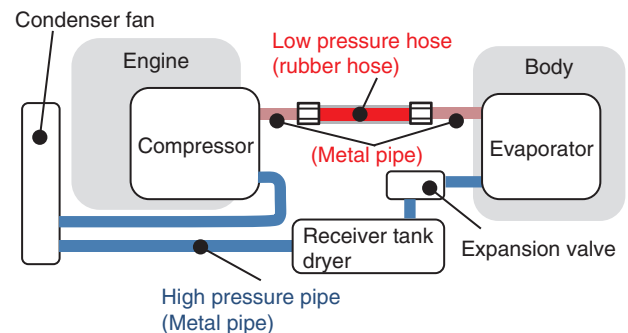


Fig. 3 Overview of car air-conditioning hose system

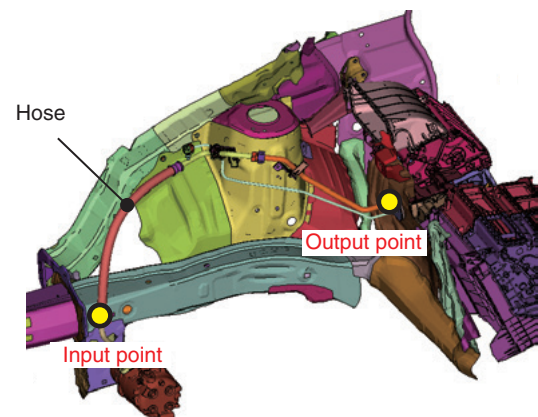


Fig. 4 Measuring points in sedan model

pressure, the hose has a multi-layered structure that includes a reinforcing layer of fiber. Transfer function measurements were made with and without internal pressure at the measuring points shown in Fig. 4. Comparison of the results, as shown in Fig. 5, indicates a change in level of 10 dB or more at the most, and it is also apparent that the transfer function varies across a wide range from approximately 150 Hz to 1000 Hz. This is thought to be due to the change in the Young's modulus and shape of the hose because of the varying magnitude of the internal pressure, and it showed that the internal pressure of the hose would need to be taken into consideration in order to determine the transfer function. For prediction of the transfer function, therefore, it was decided to reproduce a state that includes the internal pressure.

The following steps were therefore included in this technique:

- (1) Examine the physical property values and meshing conditions needed to reproduce the stand-alone hose mode in a state without internal pressure
- (2) Taking the hose created in step (1), create a model that adds the influence of internal pressure
- (3) In order to reproduce the state as installed in a vehicle, create a modeling technique that adds the pipe, body, compressor, and other surrounding components.

With regard to the body that is to be joined, particularly in step (3), use was made of existing FEM body model resources created for the purposes of other analyses. This made it unnecessary to create a large new model and reduced the time taken by analysis. After creating this technique using a medium-sized sedan model, the general applicability of the technique was verified on a compact SUV.

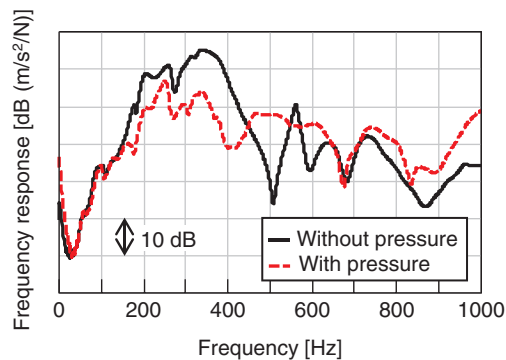


Fig. 5 Test results produced with and without pressure

4. Details of Created Technique

4.1. Creation of a Prediction Model for a Stand-alone Hose with a Multi-layered Structure

Since the hose has a multi-layered structure, as stated above, a CAE model that takes the physical properties of

each layer into consideration was created.

The hose has a diameter of approximately 20 mm, and the model as a whole was given a mesh size of 5 mm. For the meshing of each rubber portion in a radial direction, the size of each rubber layer was made finer so it could have three-layered meshes, as shown in Fig. 6. This made the model capable of precisely reproducing modes in which the hose is deformed in a radial direction.

With regard to the reinforcing layer, which is located between the other two layers, its influence on the Young's modulus of the hose is large. Therefore the reproducibility of the mode was enhanced by configuring the anisotropy in the tensile and compressive directions.

Next, starting with a hose of a straight shape that is not fixed in place, a model with a 90° bend was created and the transfer functions at the measuring points shown in Fig. 7 were calculated. Figure 8 shows the results. The reproduction precision with respect to the measurement was 2 dB of error in the transfer function level at the resonance peak. The model of the hose as a multi-layered structure that includes the hose fibers successfully reproduced the measurement with the bend of the hose also taken into consideration.

4.2. Modeling the Influence of Hose Internal Pressure

Two main factors that are influenced by the addition of internal pressure can be cited. The first is that the stress and strain are in a non-linear relationship because the hose is made from rubber that is a polymeric material, and the resulting changes in Young's modulus are an influencing

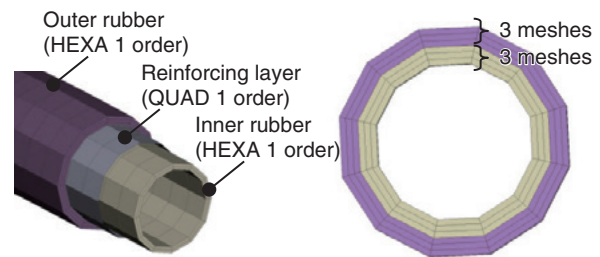


Fig. 6 Modeling of multi-layered hose

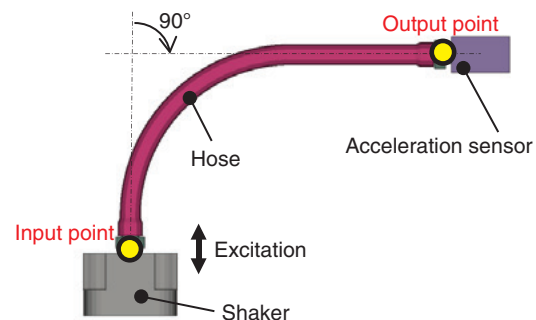


Fig. 7 Way to bend hose and measuring points

factor. The second is that the hose inflates due to pressure from the inside, and the resulting changes in shape due to varying diameter and total length is an influencing factor.

A model was first created that takes the changes in the Young's modulus and shape of the rubber hose into detailed consideration without omitting the two influence factors. The method followed was to specify the surface of the innermost side of the hose where it comes into contact with the coolant gas, and to apply pressure to that surface in order to reproduce the influence of the internal pressure. Non-linear analysis was then used to calculate the changes in the Young's modulus and shape of the hose, and the results from comparison with the model before internal pressure was added are shown in Fig. 9(a) and (b). The addition of internal pressure causes the Young's modulus and shape to change together, and it is apparent that the two influence factors have been successfully reproduced. This detailed model can be considered to fully reproduce the actual phenomenon, but even though this is a stand-alone model of the hose, the calculation took four hours or more.

The aim of this technique is to achieve a balance between calculating precision and reduction of the time taken. Therefore, as long as the calculating precision can be maintained, it is desirable to minimize as much as possible the influence factors that are taken into consideration for the purpose of shortening the time taken by analysis. Here the rate of dimensional change in diameter and total length of the hose due to the addition of internal pressure were calculated, with the results shown in Fig. 10. It is apparent that both are very small, at 1.9% and 0.3% respectively. Therefore verification was carried out to determine whether calculating precision can be maintained even in a state that ignores those deformations.

A simplified model was created that takes only the change in the Young's modulus of the rubber hose into consideration, ignoring the changes in shape. For this, the same method for applying internal pressure as described above for the detailed model was used. The changes in the

Young's modulus and shape due to internal pressure were then calculated using static analysis. The dynamic analysis that was used after that to calculate the transfer function, as shown in Fig. 9(c), incorporated only the changes in the Young's modulus. This analysis was performed without incorporating information about changes in the diameter

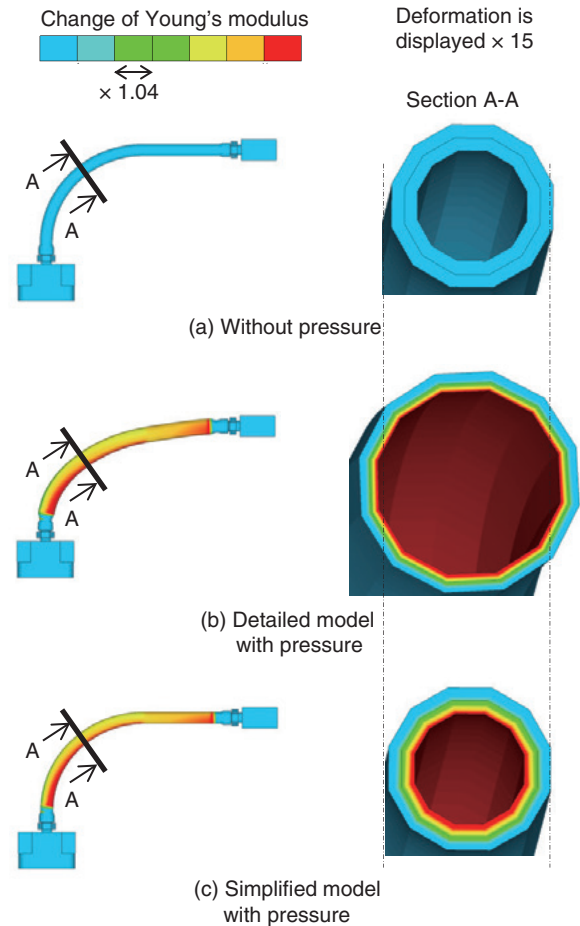


Fig. 9 Pressure effect result for each model

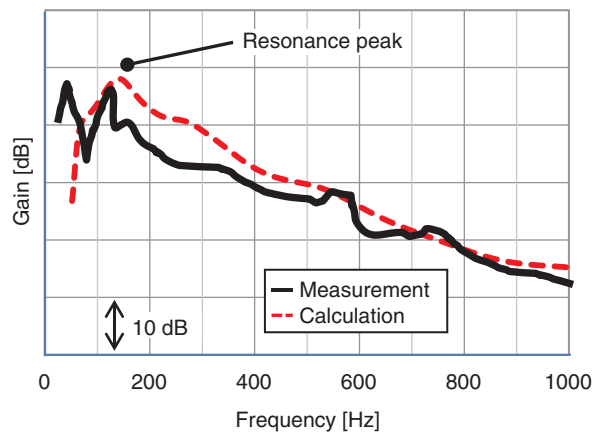


Fig. 8 Frequency response accuracy under conditions without pressure

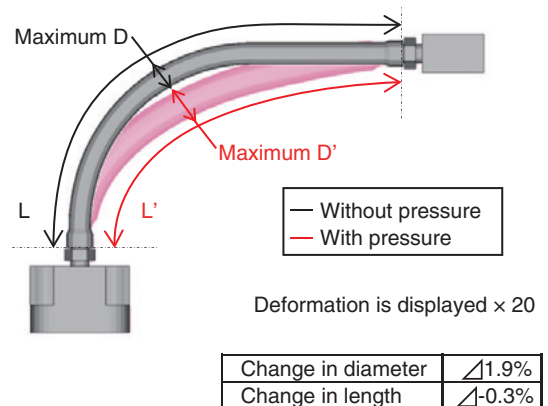


Fig. 10 Change in hose dimensions by pressure

and total length of the hose. This simplified model uses linear analysis and so was able to yield calculation results in one hour or less.

The difference between the calculation results from the detailed model and the simplified model of the transfer function are shown in Fig. 11. It is apparent that the differences in the resonance peak frequency was 1% and in the transfer function level it was 1 dB or less. Meanwhile, the calculation time of the simplified model was successfully shortened to approximately one-fourth that of the detailed model. Consequently, it was decided that for the present research, a simplified model would be adopted that takes into consideration only the change in the Young's modulus of the hose in order to maintain the minimum required calculating precision while shortening the calculation time. Figure 12 shows the precision with which the simplified model reproduces the actual measurements. At the resonance peak, the transfer function level error is 3 dB, indicating that a technique for predicting the hose transfer function with internal pressure applied has been successfully created.

4.3. Reproduction of the State as Installed in a Vehicle

The stand-alone hose model created as described up through the previous section was used to carry out prediction of the transfer function in the state as installed in a vehicle.

To reproduce the vehicle state, the pipes and clips that attach to the hose were added. The approach to the body, as described earlier, was to avoid the necessity for creating a large new model and instead to use an existing model. The present technique deals with the frequency range of vibration that is local, which means frequencies of approximately 100 Hz or higher and only in the vicinity of the hose. The rear end of the vehicle is distant from the engine compartment and so has little influence. Therefore a “cut body model” consisting only of the front end of the vehicle was used. Moreover, component mode synthesis method (CMS)^{(3), (4)} was used to join the modal models of

the body and engine to create the model. The time required for analysis was successfully shortened by these means.

Figure 13 shows the transfer function results. At the resonance peak, the reproduction precision with respect to measurement met the target by achieving reproduction precision of 2% for frequency error at the target $\pm 5\%$ value, and by achieving reproduction precision of 3 dB for transfer function level error at the target ± 3 dB value. The total time taken by analysis was 23.75 hours versus the target of 24 hours or less, so this also successfully achieved the target.

As indicated by the above, a technique was successfully created to predict the transfer function of a hose in the state as installed in a vehicle.

4.4. Verification of General Applicability

This technique was applied to a compact SUV and its general applicability was verified. Although this model vehicle differs from the medium-sized sedan model that has been covered up to the preceding section above in its engine, hose, pipe, and body, the same modeling method

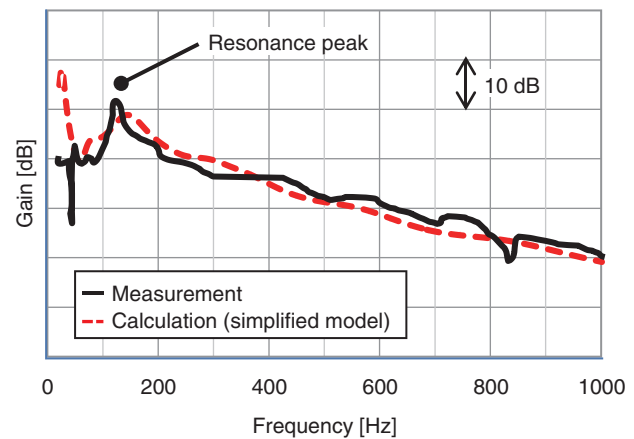


Fig. 12 Frequency response accuracy under conditions with pressure

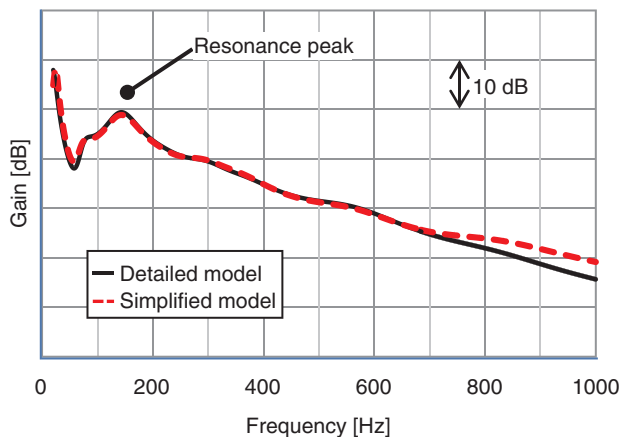


Fig. 11 Frequency response results for each model

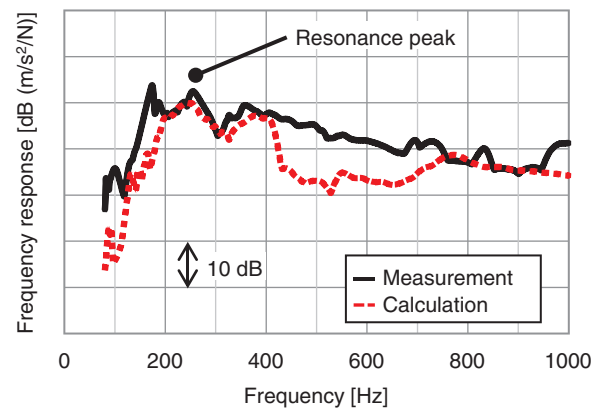


Fig. 13 Frequency response accuracy of hose model installed in sedan

was used to conduct an analysis. Figure 14 shows the measuring points and Fig. 15 shows the transfer function results.

At the resonance peak, the reproduction precision with respect to measurement met the targets at 2% for frequency error and 2 dB for transfer function level error. The total time taken by analysis was 23.25 hours, which successfully achieved the target.

This can therefore be considered to have sufficient general applicability as long as the hose layout is of the normal type used as samples. This verifies the usefulness of the created prediction technique.

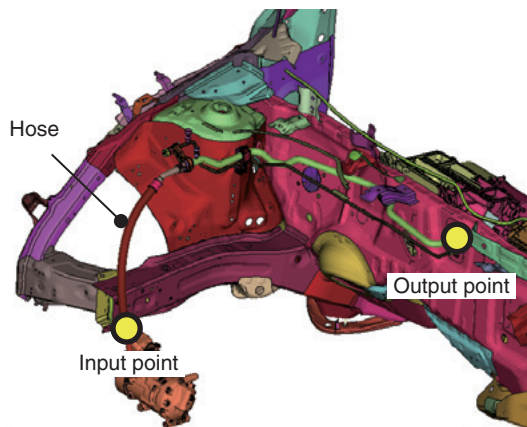


Fig. 14 Measuring points in compact SUV

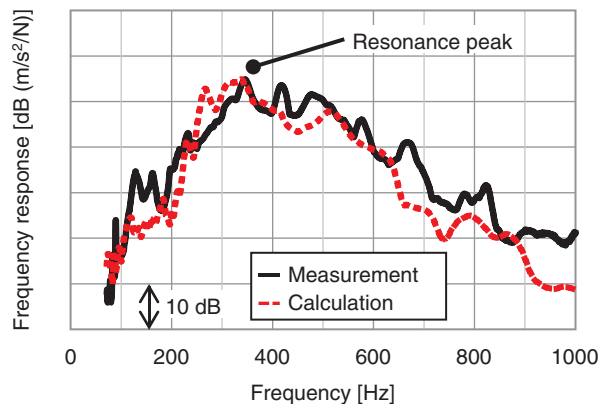


Fig. 15 Frequency response accuracy of hose model installed in compact SUV

5. Conclusion

In order to support prototype-less development in the initial development stages, a method for predicting the transmission of vibration was devised for use with low-pressure air-conditioning hose, which is one transfer path for the booming noise and engine noise that occur during

acceleration. The general applicability of this method was also verified.

In this process, the technique was also examined for its applicability to vehicle development. The following results were obtained.

- (1) In the vehicle state, the frequency error was 2% at the resonance peak and the transfer function level error was 3 dB, so vibration transmitted by the hose was successfully reproduced with a precision that presents no obstacle in vehicle development.
- (2) Measures devised for the method of analysis and simplification of the modeling kept the total time taken by analysis to 24 hours or less. The time taken by analysis was therefore successfully shortened while maintaining the calculating precision described in (1).
- (3) With regard to the body-sized model, the use of existing FEM model resources successfully shortened the time required.

As indicated by the above, a technique was successfully created for achieving sufficient precision in predicting the vibration transfer function of a hose in a state as installed in a vehicle with a view to prototype-less development using MBSE.

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