

Technology for Prediction of Contactor Noise for Electric-powered Vehicle Batteries

Akito SHIMOMURA¹Naoki TOYAMA¹Masamichi KAWABE¹Yoshimi SATO²

ABSTRACT

Electric-powered vehicles have a high-voltage battery unit mounted in the vehicle body, and the sound made by operation of the electromagnetic contactor inside the unit can be unpleasant for vehicle occupants. A method was created for predicting this noise from the excitation force of the high-voltage battery unit on its own and from the acoustic transmission characteristics of the vehicle body structure. The adoption of component-based transfer path analysis made it possible to separate vibration sources from transfer systems and predict noise in the fully assembled vehicle state by using the load transferred from the stand-alone high-voltage battery unit to the vehicle body side and a transfer function that combines the vehicle body structure transfer and the cabin acoustic transfer. A computer-aided engineering model was also created for predicting the load from the stand-alone high-voltage battery unit based on the load from the junction board, which is a sub-unit of it. This made it possible to predict the excitation force of the high-voltage battery unit at the drawing stage. By means of the above technology, it has become possible to consider noise evaluation in the fully assembled vehicle state at the performance design stage.

1. Introduction

Calls to reduce the burden on the environment from automobiles have been heightening in recent years. Every automobile manufacturer has been taking measures to reduce CO₂ emissions by enhancing fuel economy performance and by developing and popularizing electric-powered vehicles.

Honda has been developing a variety of electric-powered vehicles to promote their popularization^{(1), (2)}. These electric-powered vehicles are equipped with a high-voltage battery unit (hereinafter, unit)⁽³⁾⁻⁽⁵⁾ for the purpose of storing electrical energy in batteries. Installed inside the unit is an electromagnetic contactor, which is a control device that turns the current on and off in order to supply electric power. It operates when the vehicle starts moving and when the vehicle comes to a stop. The engine is normally stopped when the vehicle starts moving, and the background noise level is low, so that the sound of the unit operating is heard as an unpleasant noise. Because this noise has been evaluated in a fully assembled vehicle state, issues often emerge in later stages of development that leave no option but to rework development or take additional measures.

There is demand, therefore, for the creation of technology to predict noise in the initial stages of development.

Transfer path analysis (TPA) is one method used for analyzing this kind of noise. The noise in a fully assembled vehicle state can be predicted by multiplying together the input from the unit, which is the vibration source, and the structural acoustic transfer function on the vehicle body side, which is the response system. When the input system and response system are close to being rigidly connected, the method commonly used in traditional TPA to identify the input is to use a transfer function matrix for the response system together with the response obtained when in actual operation. Measurements are made using the actual vehicle body and unit, however, so this method cannot be applied in the initial design stages when a prototype unit does not exist.

For this paper, therefore, a method was created for predicting noise in a fully assembled vehicle state by using component-based TPA to allow the unit and the vehicle body to be evaluated separately. This approach was used together with computer-aided engineering (CAE) to create a method for predicting input from the unit without using a prototype unit.

¹ Honda Motor Co., Ltd.

² Estech Corp.

2. Electromagnetic Contactor Operating Noise

2.1. Excitation Caused by Electromagnetic Contactor

The electromagnetic contactor is one of the control devices used to turn large electric currents on and off. Figure 1 shows a schematic view of this electromagnetic contactor. It controls the on-off state of the electric current by using electromagnetic force to change the position of a movable iron core and open or close a contact. The contact that occurs when this is done is a vibration source, and the vibration is transmitted from the unit to the vehicle body, producing noise.

2.2. High-Voltage Battery Unit Configuration

Figure 2 shows an example of unit components. The electromagnetic contactors are mounted on the junction board, which has the safety function of breaking electrical connections and current flow. The configuration has this junction board attached to the battery frame, and the unit including this component attached to the vehicle body frame.

2.3. Operating Noise in a Fully Assembled Vehicle

The operating noise of an electromagnetic contactor in a fully assembled vehicle is an impact noise that occurs for a brief period of time. Figure 3 shows the results from frequency analysis of this operating noise at a vehicle occupant's ear location. It is apparent that there is a peak from around 100 Hz to 600 Hz. Taking into account the frequency range close to this peak together with the fact that the lower limit of the audible frequency range is generally about 20 Hz, the frequency range for analysis was set from 20 Hz to 1000 Hz.

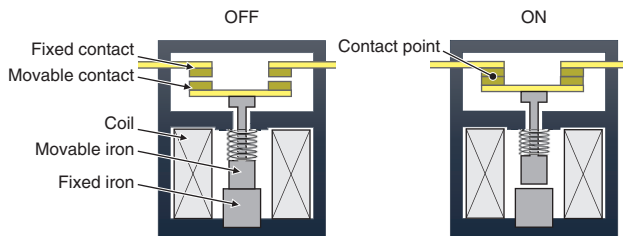


Fig. 1 Schematics of electromagnetic contactor

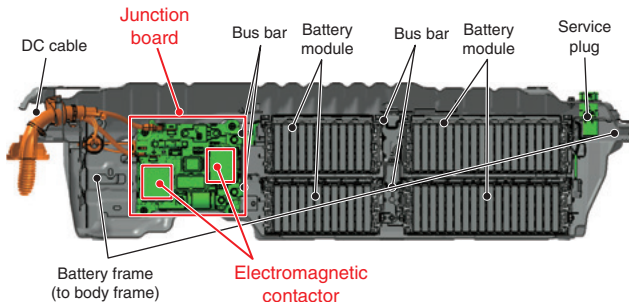


Fig. 2 High-voltage battery unit components

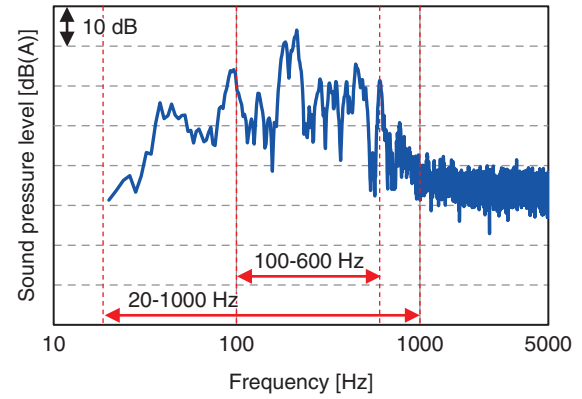


Fig. 3 Cabin noise of electromagnetic contactor

3. Component-Based TPA

3.1. Differences from Traditional TPA

TPA has long been in frequent use for the analysis of noise and vibration. This is a method for analyzing the degree of contribution by sound sources and the respective transmission paths based on input from the engine, motor, and other such vibration sources together with the structural acoustic transmission characteristics of the vehicle body and so on that form the response system^{(6), (7)}.

Component-based TPA is a method that makes it possible to measure input from the unit discretely when it is detached from the response system on the vehicle body side⁽⁸⁾. In traditional TPA, measurements of unit input had to be made with the unit and the vehicle body in a combined state. In component-based TPA, measurements of structural acoustic transmission characteristics are made with the unit and the vehicle body in a combined state, allowing measurement of unit input from the unit, detached from the vehicle body side. Table 1 shows a comparison with traditional TPA. This has become a very actively utilized method of analysis in recent years because it allows a target load value to be set for the unit and it also fits with the ongoing trend toward accelerated flow of model-based development.

3.2. Transmission Force from Unit

Three main methods are known for measuring input loads in component-based TPA⁽⁹⁾. The first is the direct force method, in which the unit is mounted rigidly in place and the load transmitted from the vibration source is measured directly. The second is the hybrid method, in which the unit is fixed in a jig, and the load it transmits is measured and combined with the response to transmission in that system to identify the equivalent load. Third is the free velocity method, in which the unit is in a free state, and the response transmitted from the vibration source is measured and converted into load. Figure 4 shows these methods in schematic form. Although the second and third methods are frequently used, they require the acquisition

Table 1 Traditional TPA and component-based TPA

Method	Input force (F)	Transfer function (H)
Traditional TPA	Contact force	Unit separation
Component-based TPA	Blocked force	Unit combine

of a transfer function for separate measurement systems, which necessitates a procedure to convert the measurement load to equivalent external force. With the first, direct force method, mounting the unit rigidly in place does become an issue, but since the measured placement reaction force can itself be taken as the equivalent external force, this method has the advantage of a simpler measurement procedure.

The theory of component-based TPA in the direct force method can be explained as follows. The equation of motion for the system made up of input system and response system is considered in dynamic stiffness notation. This dynamic stiffness is fixed for each transmission path. If the notation is D_{sr} , for example, then this means a dynamic stiffness that is derived from the response-side response during source-side excitation. This is thought of as being in a combined state (non-operation), being in a combined state (under operation), and being in a rigidly-joined state (under operation), as shown in Fig. 5, and the placement reaction force for the rigidly-joined state (under operation) is derived from each equation of motion.

In a combined state, the equation will be as follows:

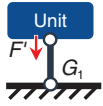
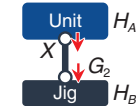
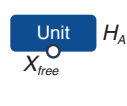
$$\begin{bmatrix} D_{rr} & D_{rs} \\ D_{sr} & D_{ss} \end{bmatrix} \begin{bmatrix} x_r \\ x_s \end{bmatrix} = \begin{bmatrix} f_r \\ f_s \end{bmatrix} \quad (1)$$

D : Dynamic stiffness s : Source
 x : Displacement r : Response

An equation is also set up similarly and expanded for the combined state (under operation).

$$\begin{bmatrix} D_{rr} & D_{rs} \\ D_{sr} & D_{ss} \end{bmatrix} \begin{bmatrix} x_{ra} \\ x_{sa} \end{bmatrix} = \begin{bmatrix} 0 \\ f_s \end{bmatrix} \quad (2)$$

s_a : Source in operating state
 r_a : Response in operating state

(1) Direct Force	(2) Hybrid	(3) Free Velocity
		
$F' = G_1$	$F'^{eq} = G_2 + H_A^{-1} \cdot X$	$F' = H_A \cdot X_{free}$

G : Response force
 X : Receiver

Fig. 4 Force measurement of component-based TPA

$$x_{sa} = D_{ss}^{-1} (f_s - D_{sr} x_{ra}) \quad (3)$$

$$D_{rs} D_{ss}^{-1} f_s = D_{rs} D_{ss}^{-1} x_{ra} - D_{rr} x_{ra}$$

Another equation is set up similarly and expanded for the rigidly-joined state (under operation).

$$\begin{bmatrix} D_{rr} & D_{rs} \\ D_{sr} & D_{ss} \end{bmatrix} \begin{bmatrix} 0 \\ x_{s0} \end{bmatrix} = \begin{bmatrix} f_{r0} \\ f_s \end{bmatrix} \quad (4)$$

s_0 : Source in rigid state

$$f_{r0} = D_{rs} D_{ss}^{-1} f_s \quad (5)$$

Equation (5) is derived from Eq. (4). Plugging Eq. (3) into Eq. (5) yields the placement reaction force f_{r0} .

$$f_{r0} = (D_{rs} D_{ss}^{-1} D_{sr} - D_{rr}) x_{ra} \quad (6)$$

Next, an equivalent external force that reproduces the response of the combined state (under operation), of the kind shown in Fig. 6, is envisaged.

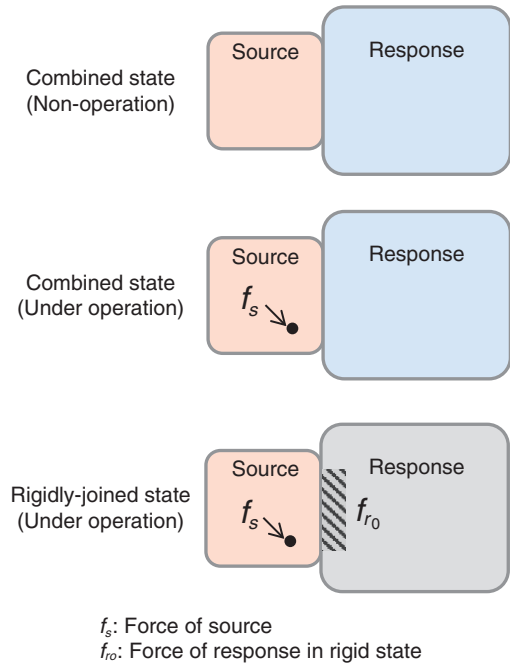


Fig. 5 Equation of motion

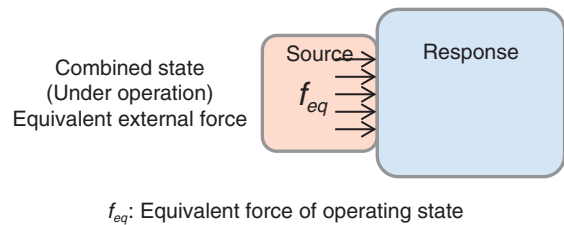


Fig. 6 Equation of motion by equivalent external force

An equation of motion in dynamic stiffness notation is set up, yielding Eq. (7) with respect to the equivalent external force.

$$\begin{bmatrix} D_{rr} & D_{rs} \\ D_{sr} & D_{ss} \end{bmatrix} \begin{bmatrix} x_{ra} \\ x_{sa} \end{bmatrix} = \begin{bmatrix} f_{eq} \\ 0 \end{bmatrix} \quad (7)$$

$$f_{eq} = -(D_{rs}D_{ss}^{-1}D_{sr} - D_{rr})x_{ra}$$

It is apparent that this equivalent external force is opposite in direction but equal in size to the placement reaction force of Eq. (6). The equivalent external force calculated from the transfer function matrix when combined is, therefore, equal to the reaction force when the vibration source is positioned at the point where combined.

When using the direct force method, the input load from a unit that is rigidly connected and fixed in place in a jig can be measured and that value used as the component-based TPA input value.

3.3. Application to Electromagnetic Contactor Operating Noise

The operating noise of an electromagnetic contactor will be described first in terms of the transmission path. As shown in Fig. 7, the vibration of the electromagnetic contactor when it operates is transmitted from the junction board, which is a sub-unit, to the unit. Up to this point is taken as the input side. The unit is fastened to the vehicle body frame with bolts. The vibration is transmitted from this join to the vehicle body and to the cabin interior space. If the characteristics of input from the unit and the structural acoustic transmission characteristics of the vehicle body and cabin interior space are known, then the cabin noise can be predicted using TPA. The load on the join can be substituted with the unit load when rigidly connected, as discussed in the preceding section.

3.4. Test Configuration

The configuration of the unit test of electromagnetic contactor operating noise is described here. In order to confirm that verification can be performed with the unit detached from the vehicle body side, the testing was implemented on a unit installed at a different location in the vehicle body. Figure 8 shows unit measurement. The unit

is fixed in place on a jig using bolts and fastened to it under the specified torque conditions for fastening to the vehicle body side. The fixture used here was designed with a higher degree of stiffness so that the lowest order of natural frequency could be three times or higher than 1000 Hz. This keeps vibration of the jig from influencing the analysis target frequencies from 20 Hz to 1000 Hz. Load sensors were also placed between the unit's joins to the frame and the jig to measure the placement reaction force from the unit to the jig when an electromagnetic contactor operates.

3.5. Test Results

The results from verification of unit evaluation are described here. Figure 9 shows the results from measurement of unit load by the installed location of the unit in the vehicle body. Differences in the load paths within the unit yielded corresponding differences in the frequency characteristics of the load.

Next, Figs. 10 and 11 show the noise prediction results from unit measurements by unit installed location in the vehicle. These are compared with the results for noise in a fully assembled vehicle. This successfully confirmed that the predicted noise represented the peaks of sound from 100 Hz to 600 Hz in fully assembled vehicle noise, regardless of the installed location. The noise levels at the frequencies from 20 Hz to 1000 Hz targeted for analysis were also confirmed.

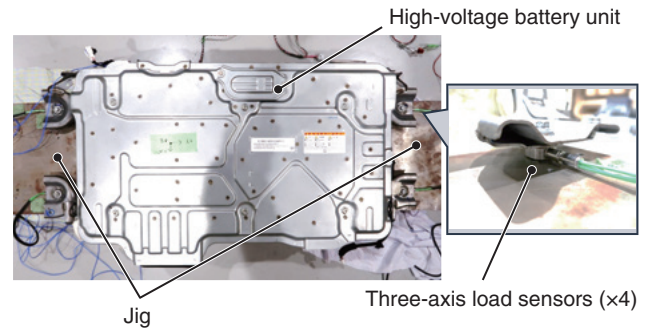


Fig. 8 Force response test of high-voltage battery unit

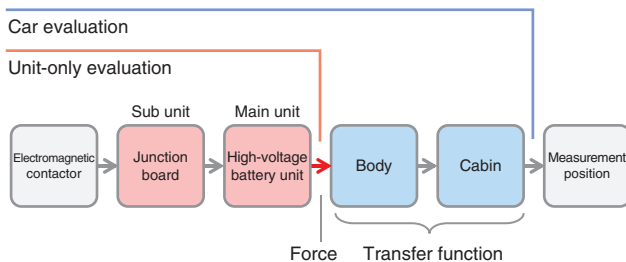


Fig. 7 Transmission path of contactor noise

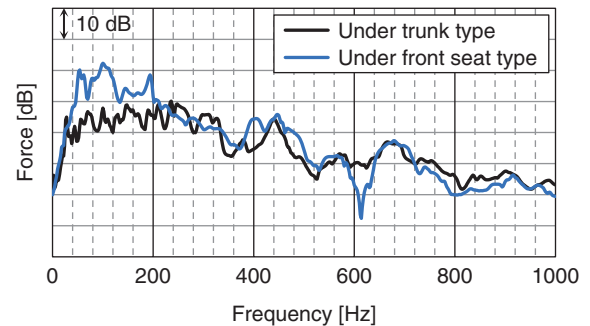


Fig. 9 Input force from unit

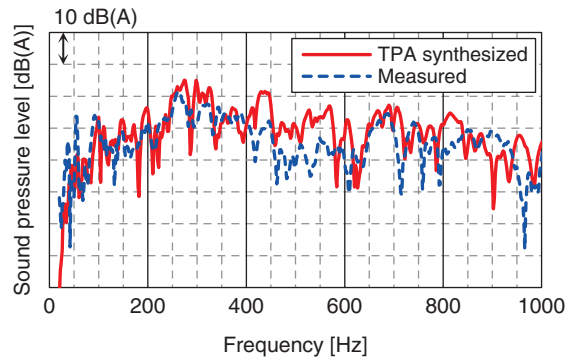


Fig. 10 Sound pressure level (Under trunk type)

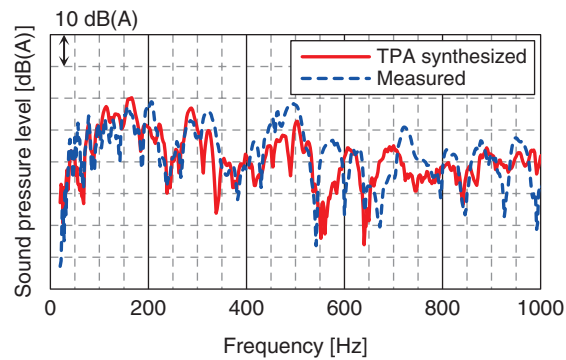


Fig. 11 Sound pressure level (Under front seat type)

4. Unit Transmission Force According to CAE

4.1. CAE Modeling Method

For the operating noise of an electromagnetic contactor in a fully assembled vehicle state, the unit load can be made the target value by calculating back from the target value for cabin noise based on TPA results. If it were possible to predict those load characteristics by CAE at the unit design stage, then development could be advanced more efficiently by putting it on a non-prototype basis. A CAE model was thus created that would calculate the load transmitted to the vehicle body from a unit. The actual measurement values of load transmitted from the junction board to the unit were used in the input conditions.

Figure 12 shows a model based on the finite element method (FEM). The junction board has a complex shape, so it was expressed using concentrated mass elements to reduce the burden of calculation, and the frequency response analysis was implemented with the unit fixed rigidly in place and the boundary conditions of the unit join portions taken as totally constraining.

Using actual measurement values for the input from the junction board, analysis of the load transmission was carried out with loads from two units having different structures,

unit A and unit B. The main structural difference was in the location where the junction board was attached to the battery frame. Figure 13 shows a schematic view. Unit A has the junction board attached to the side surface of the unit close to the vehicle body join. Unit B has the junction board attached to the rear of the unit. In order to verify the validity of this approach, the testing in coordination with CAE was carried out with equal rigid combined state, as unit tests (Fig. 8), and the results were compared.

4.2. Results of Verification by CAE

The CAE analysis results for differing unit loads produced by the same input conditions as compared with actual measurement results are shown in Figs. 14 and 15.

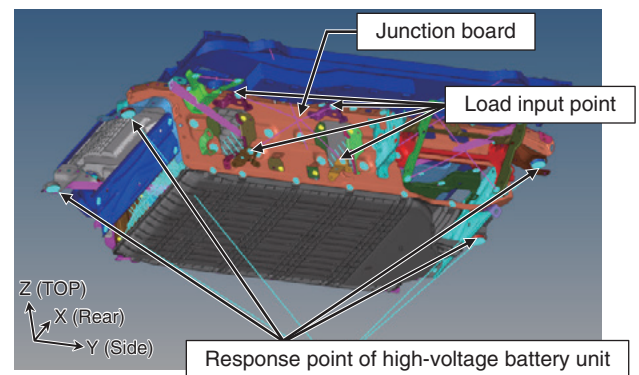


Fig. 12 CAE modeling of high-voltage battery unit

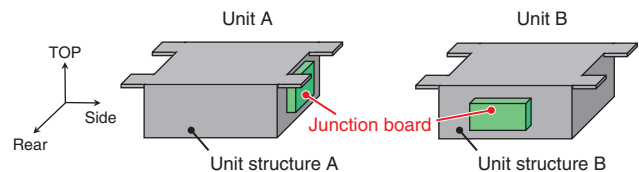


Fig. 13 Junction board mounting position

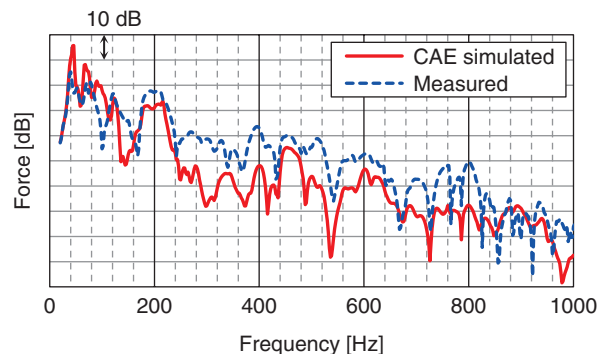


Fig. 14 Force CAE-analysis (unit A)

The difference between unit A and unit B in junction board installation location resulted in differing vibration modes in the battery frame during operation of the electromagnetic contactors. With unit A, there was a peak due to resonance in the vicinity of 200 Hz. Similarly, with unit B, there was also a resonance point in the vicinity of 200 Hz, but its vibration characteristics were distributed more widely across the entire range. This difference can also be observed in the frequency characteristics of the join load values of the units. The CAE results reproduce this feature well, confirming the validity of the CAE modeling here.

The unit load values analyzed by CAE were also used to predict noise in the fully assembled vehicle state. The structural acoustic transfer functions for the vehicle bodies use the actual measurement values for vehicles of the same class. The results for noise in the fully assembled vehicle state, for noise predicted by calculation from unit testing, and also for noise predicted by calculation from CAE predicted unit load values were compared. The blue dotted line shows values for noise measured in the fully assembled vehicle state. The green dotted line shows values for noise predicted from unit testing. The red solid line shows values for noise predicted from the unit load obtained by CAE. The results for unit A in Fig. 16 show that the resonance point

in the vicinity of 200 Hz is successfully reproduced. It is apparent from the results for unit B in Fig. 17 that the broad distribution from 200 Hz to 700 Hz has been reproduced. The sound pressure levels in each frequency band have been successfully verified, and this confirms the validity of CAE model utilization in investigations of design addressing noise.

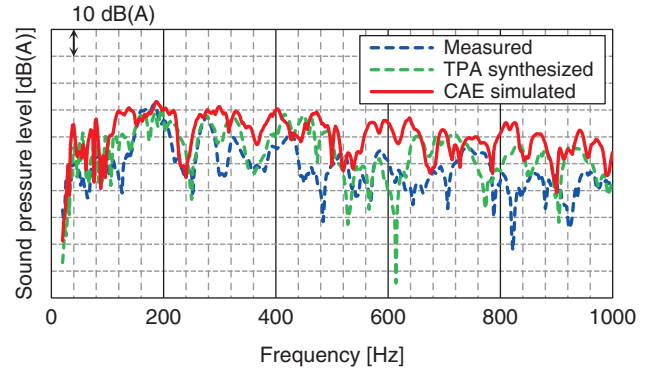


Fig. 17 CAE simulated noise (unit B)

5. Conclusion

- (1) The prediction of noise in the fully assembled vehicle state was successfully accomplished by using the direct force method of component-based TPA to isolate the unit that is the vibration source from the vehicle body side and then using the unit load measurements with the structural acoustic transmission characteristics of the vehicle body.
- (2) A model that utilizes CAE was created to analyze the unit transmission force, and noise in the fully assembled vehicle state was successfully predicted from the results of junction board load measurement.

The present investigation has enabled advance development of the unit in the initial stages when no fully assembled vehicle exists by working from target values for noise in the fully assembled vehicle state and substituting the target values for the unit load. A model was created that predicts the unit load by means of CAE. Prediction of noise in the fully assembled vehicle state from the junction board load measurement results has become possible at a stage when a unit prototype does not exist, allowing even earlier investigation of design.

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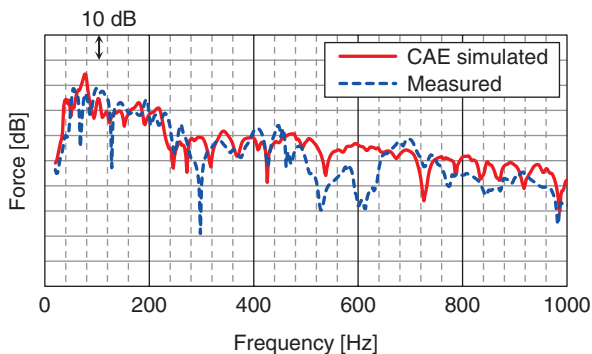


Fig. 15 Force CAE-analysis (unit B)

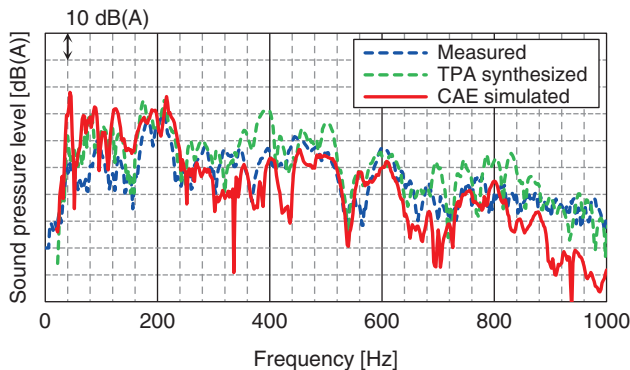


Fig. 16 CAE simulated noise (unit A)

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■ Author ■

Akito SHIMOMURA



Naoki TOYAMA



Masamichi KAWABE



Yoshimi SATO