

Hybrid SEA Modeling Scheme for Analysis of High-frequency Noise in Passenger Car

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ABSTRACT

A Hybrid SEA modeling method has been developed and applied to increase the accuracy of the SEA model for a passenger car. This paper will discuss the detailed workflow of the modeling method and the method employed to verify the accuracy of the model during development. In addition, to provide an example of the high level of accuracy of the results, the paper will discuss a road noise (interior cavity sound pressure level) analysis conducted with a complete vehicle SEA model constructed using the method.

1. Introduction

Reduced noise in the interior cavity is one of the prime selling points for automobiles. In order to consider the noise and vibration phenomena in the early stages of the design of an automobile, it is essential to create an analytical model capable of accurately expressing the dominant paths for transmission of acoustic and vibratory power, which comes to the cabin from a variety of sources. Using this kind of model allows one to design in features for reducing interior cavity noise due to road noise. However, the large number of both vibration sources and transfer paths complicates noise and vibration issues.

Nowadays, it has become possible to use Statistical Energy Analysis (SEA) to analyze the propagation of noise in the 400 – 5 000 Hz frequency range through both acoustic spaces in the vehicle and its structure^{(1)–(3)}. In addition, there are cases⁽⁴⁾ showing how SEA has proven effective for solving vibration issues in the 200 – 400 Hz frequency band. However, in the past, it had not been possible to model propagation from sources to the interior cavity through the main transfer paths of the air and structural members.

This report describes details of analyses and the verification of a Hybrid SEA model of an automobile body capable of predicting transfer paths for road noise in the 200 – 5 000 Hz frequency range. The model precisely predicts interior cavity noise by accurate reproduction of the main transfer paths through the air and through the structure.

2. Method of Hybrid SEA Modeling

The “Hybrid SEA model” proposed in this report is a combination of a conventional analytical SEA model and a test-based SEA model which accurately reproduces the energy flow that occurs in an actual automobile. This section of the report describes the process of assembling the model, in the following six steps:

- (1) Analytical SEA model is constructed.
- (2) Input subsystems are defined.
- (3) Main transfer path network is graphed.
- (4) SEA parameters are set on the basis of test measurements.
- (5) The obtained SEA parameters are written to the analytical SEA model created in (1).
- (6) Hybrid SEA model is created.

The processes in the steps are summarized in the above order.

2.1. Construction of Analytical SEA Model

Each subsystem is defined so that it contains a sufficient number of modes in the analytical frequency band. An actual finished vehicle can be divided into about 100 structural subsystems and 20 acoustic subsystems. Since subsystems can be defined where SEA parameters cannot be measured, more subsystems may be defined in this stage than could be defined in the test-based SEA model.

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SEA parameters are theoretically determined for the defined subsystems to create the model. The commercially available package AutoSEA-2 was used for this step.

2.2. Definition of Input Subsystems

The input subsystems are selected. In an actual finished vehicle, 14 subsystems were selected from among the acoustic (Figs. 1 and 2) and the structural subsystems (Fig. 3) as input subsystems. The total number of subsystems and input subsystems depends on the vehicle model (sedan, 1 BOX, 2 BOX) and the type of suspension.

2.3. Construction of Main Transfer Path Network Diagrams

The main transfer path is selected for each input subsystem defined in section 2.2. Next, a diagram of the network for each path is created on the basis of the analytical SEA model results. The example in Fig. 4 is the network diagrams for power inputs into the front damper housing (Dpr housing up).

2.4. Measurement of SEA Parameters

The energy ratios between each of the subsystems in the constructed network diagram are measured. The ratios are used to find the Coupling Loss Factors (CLF) between each subsystem pair. The Total Damping Loss Factor (TDLF) for each subsystem is also measured, using the decay rate method^{(3), (4)}, at the same time as the energy ratios.

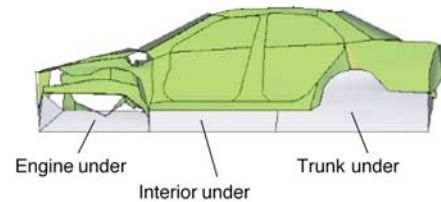


Fig. 1 Acoustic input subsystems (under car body)

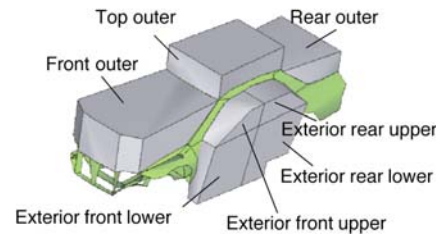


Fig. 2 Acoustic input subsystems (around car body)

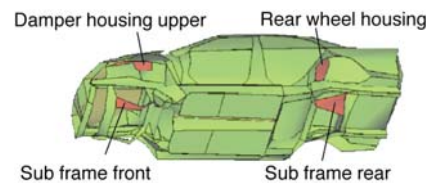


Fig. 3 Structural input subsystems

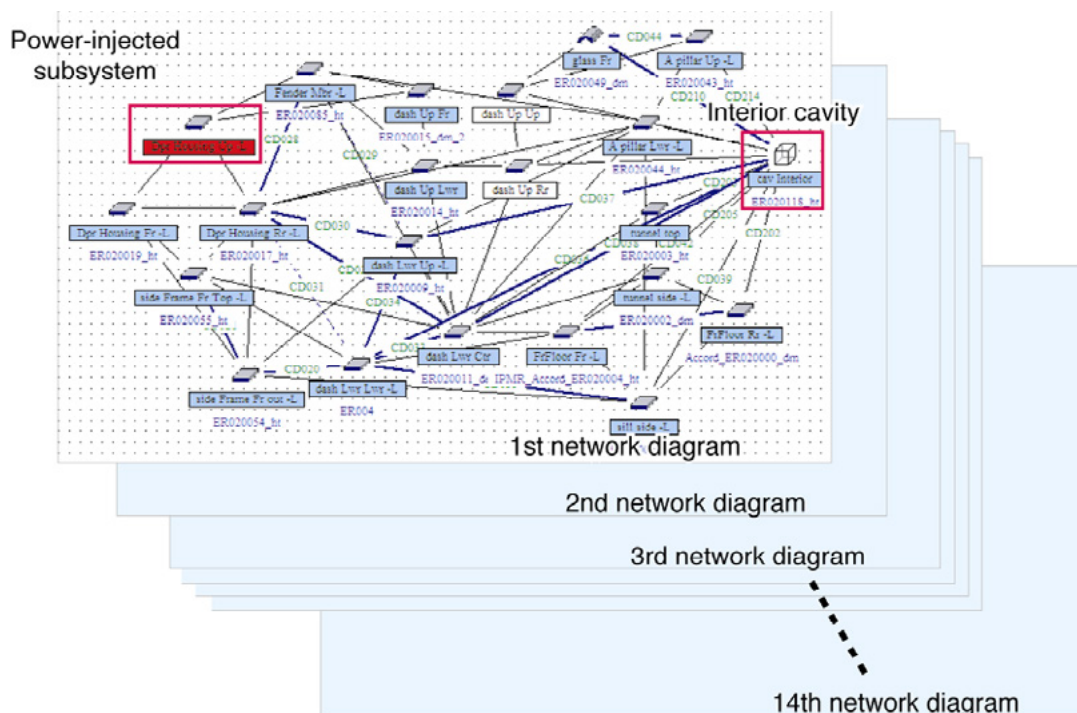


Fig. 4 14 Network diagrams ("Dpr housing up- left" is power injected subsystem)

2.5. Writing Obtained SEA Parameters to Analytical SEA Model

The parameters for the constructed analytical SEA model are converted to the corresponding parameters (TDLF, CLF) measured in the test-based SEA model.

2.6. Creation of Hybrid SEA Model

The energy ratios between each input subsystem and other subsystems are calculated using the models created in 2.5. The resulting values for energy ratios are then compared with the values measured in 2.4. In Fig. 5, the first number appearing under each subsystem name in the network diagram is the test-determined value in dB, and the second number shows the differences in dB between the test-determined value and the calculated value.

The CLF's are adjusted in order to minimize the magnitude of the differences. A "Hybrid Process" is used to adjust CLF. The Hybrid Process is performed until all the differences are reduced to within ± 3 dB. Figure 6 shows a network in which the differences in energy ratio have been sufficiently minimized. With the completion of the above steps 2.1 – 2.6, the Hybrid SEA model is complete.

3. Verification of Accuracy

The predicted values and the measured values of the energy ratios of each subsystem are compared as the first step in verifying the accuracy of the SEA model by the Hybrid Process. Next, the interior cavity sound pressure levels resulting from road noise at 80 kph are compared between

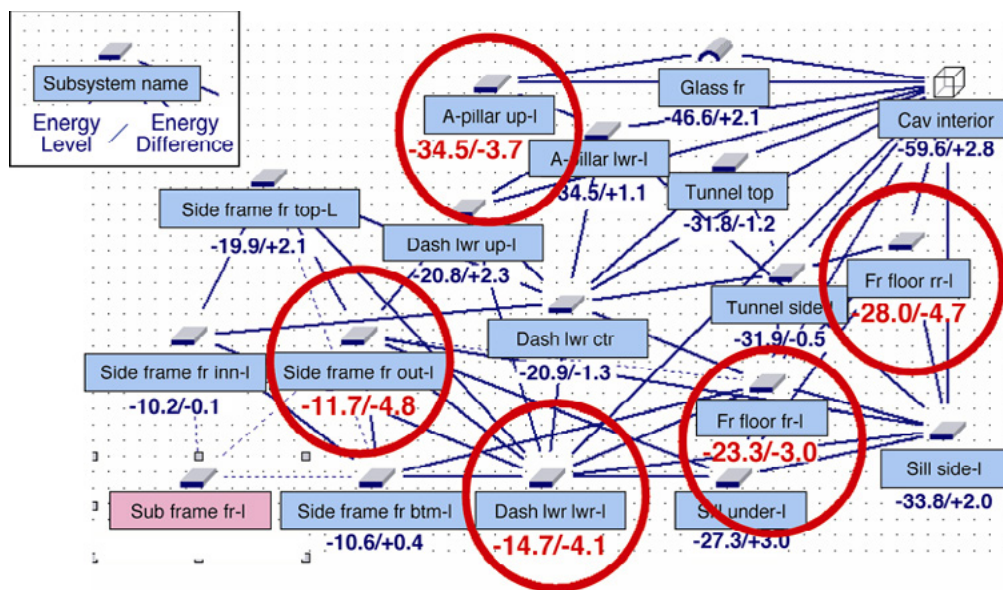


Fig. 5 Network diagram with difference of energy ratio (before hybrid process)

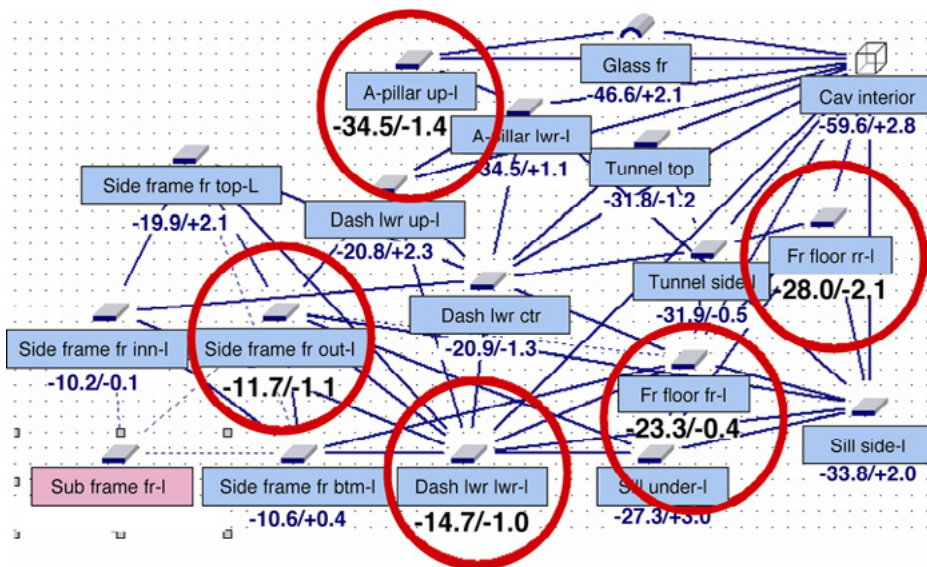


Fig. 6 Network diagram with correct energy flow (after hybrid process)

the predicted values and the measured values. The results of the comparison are described below.

3.1. Comparison of Energy Ratios between Subsystems

The first example shows the energy ratios for the floor front, a structural element, and the interior cavity, an acoustic space, as a result of input to the front sub-frame (Fig. 7a).

From Fig. 7a, it is clear that the energy flow between the structural subsystems have been reproduced within ± 3 dB at frequencies above 200 Hz. Also, from Fig. 7b, it is clear that the energy flow between the structural subsystem and the acoustic subsystem have been reproduced within ± 3 dB at frequencies above 200 Hz. Next, as an example of energy flows between acoustic subsystems, Fig. 8 shows the results for acoustic propagation from interior-under cavity to interior cavity. These findings also show a correlated model of the energy flow between the acoustic subsystems of within ± 3 dB above 200 Hz.

3.2. Comparison of Predicted and Measured Levels of Interior Cavity Sound Pressure Levels

In order to verify accuracy of the SEA model constructed using the hybrid process, road noise generated by inputs during driving at a speed of 80 kph was analyzed. The predicted interior cavity sound pressure levels were compared with the measured levels. Figure 9 provides the results of the comparison.

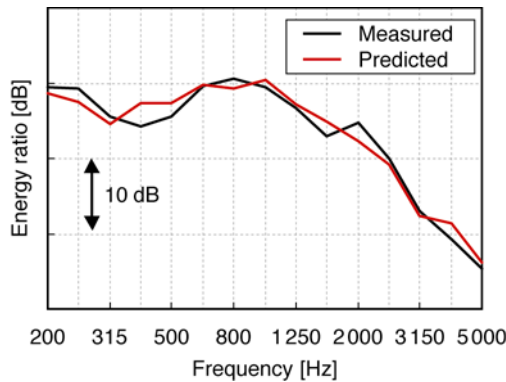


Fig. 7-a Energy ratio (Floor front/Front sub frame)

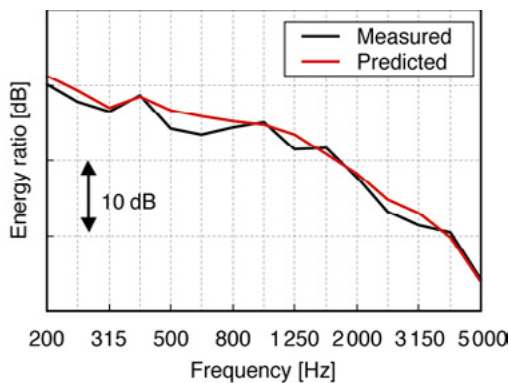


Fig. 7-b Energy ratio (Interior cavity/Front sub frame)

The results confirmed that the differences are consistent within ± 3 dB.

4. Uniqueness of Solutions

The method proposed here succeeded in accurately predicting interior cavity noise pressure level due to road noise. However, the authors had defined the uniqueness of the model solution by reproduction of the vibration and noise characteristics, including reproduction of the dominant power paths, by the constructed Hybrid SEA model in response to road noise. The authors also conceived that verifying the uniqueness is an important element for assessing the model's accuracy⁽⁶⁾. The main input correlation coefficient r_1 , a measure of the solution accuracy for power flow between subsystems, was defined as shown in Eq. (1). Similarly, the total correlation coefficient R , which used r_1 values, was defined as in Eq. (2)⁽⁶⁾.

$$r_1 = \frac{n_1}{N_1} W_1 \quad (1)$$

$$R = \sum_{i=1}^M r_i \quad (2)$$

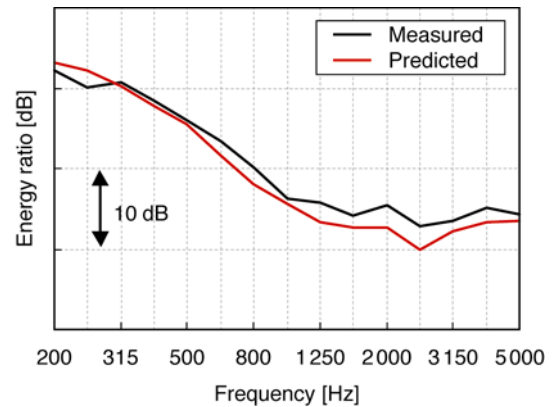


Fig. 8 Energy ratio (Interior cavity/Interior under cavity)

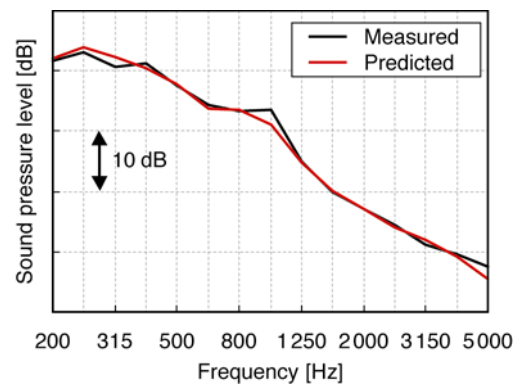


Fig. 9 Interior cavity sound pressure level (road noise analysis 80 km/h)

Here, n is the number of subsystems common to both the main input found by the test model and the main input found by the hybrid SEA model in the specified frequency band. N is the number of all the subsystems which do not receive power inputs. W_i is the contribution of the interior cavity noise made by the i^{th} main input, to the total noise. M is the total number of contributors.

As an example of this calculation, consider the transfer paths shown in Fig. 10. Here, $n = 2$ (SS2, interior cavity), $N = 6$ (SS1 – SS5, interior cavity). When 0.9 is selected as the most important input, the main input correlation coefficient r_1 in Eq. (1) is 0.3. (The solid lines in Fig. 10 represent the main input predicted by Hybrid SEA, the dashed lines, the main input according to the test model.) The verification was carried out by comparing the test-based SEA, whose accuracy for specifying the transfer paths is increased in stages with a Hybrid SEA model created by the method proposed above. The test-based SEA model was used for comparison in the 3-stage method described below, by progressive tuning of the energy ratio differences.

- Test Model 1: A model with consistent characteristics was constructed in the method described above, using only the CLF characteristics for acoustic radiation from all the panels directly adjoining the interior cavity.
- Test Model 2: A model was created whose inter-subsystem energy ratio differences were within ± 0.5 dB of measured results for the paths from the four dominant subsystems affecting the interior cavity which accounted for approximately 90% of the input into the interior cavity.
- Test Model 3: Test Model 2 was further refined to reduce the energy ratio difference from the fifth most dominant subsystem to within ± 0.5 dB.

Next, the interior cavity road noise levels were compared between Test Model 1 and the Hybrid SEA model (source of the “Predicted” figures in Fig. 11) and an actual test vehicle. Both models (Fig. 11) showed levels within ± 3 dB of results from an actual automobile; however, they showed significantly different contributions to the interior cavity from adjoining panels (analytical results for contributions at 200 Hz, Fig. 12). This illustrates that even if a good match with measured interior cavity levels seems to have been obtained, it is misleading; there is not some single unique model that can provide this. This indicates that the Hybrid

SEA model must be confirmed to reproduce the dominant power transfer paths that exist in the actual vehicle.

That confirmation is illustrated below using the total correlation coefficient R , defined above, to confirm the analytical accuracy of the power transfer paths. Figures 13 and 14 show R for Test Models 1, 2 and 3 for propagation through structural members. Figure 13 shows the R values for structure-borne noise from the front-left side of Front Subframe, and Fig. 14 shows those for noise from the left side of the Front damper housing.

These results indicate that R of Test Model 3 approaches unity at frequencies above 1 kHz and remains above 0.8 at lower frequencies. Figure 15 shows a comparison between Test Model 3 and the Hybrid SEA model for indicated power contributions from panels adjoining the interior cavity.

This indicates a superior correlation, in comparison to the results presented in Fig. 12. Not only can the Hybrid SEA model constructed by the proposed method provide accurate predictions of interior noise, actual power flows are also well reproduced. This model was therefore considered to be effective for reproducing road noise.

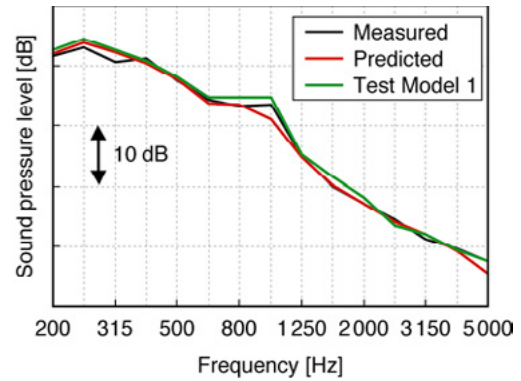


Fig. 11 Interior cavity sound pressure level for main transfer path (road noise analysis 80 km/h)

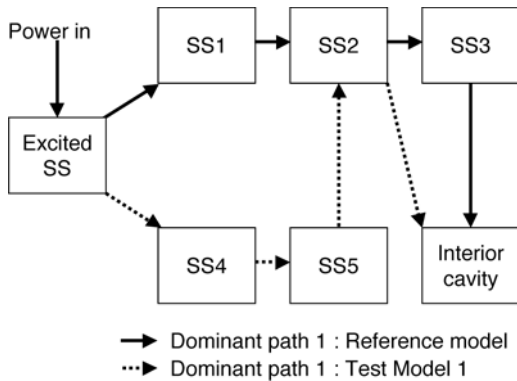


Fig. 10 Simple model for dominant power path investigation

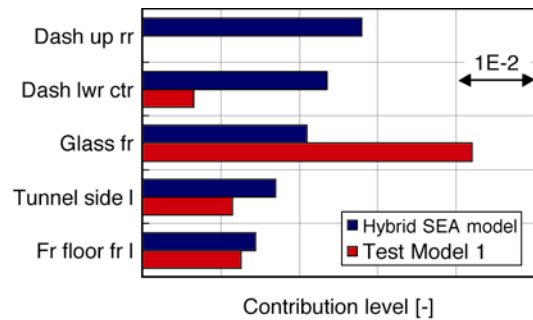


Fig. 12 Power contribution to interior cavity (before hybrid process)

5. Example of Application of Analysis

5.1. Separation of Contributions by Structural Members and Acoustic Spaces to Interior Cavity Noise

An attempt was made to distinguish between structural inputs and acoustic inputs to road noise using the Hybrid SEA model described above that is capable of identifying the unique solution to acoustic issues. First, the structure-borne cavity noise was estimated; then, the air-borne cavity noise was estimated. The results are shown in Fig. 16.

The results indicate that the structural contribution is higher up to about 500 Hz, and the acoustic system accounts for most noise at higher frequencies. This expresses the qualitative character of automobile road noise very well.

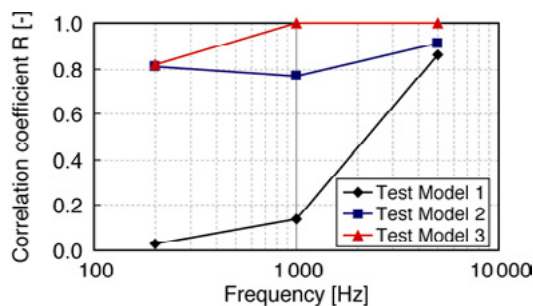


Fig. 13 Correlation coefficient (from Sub frame fr-I to Interior cavity)

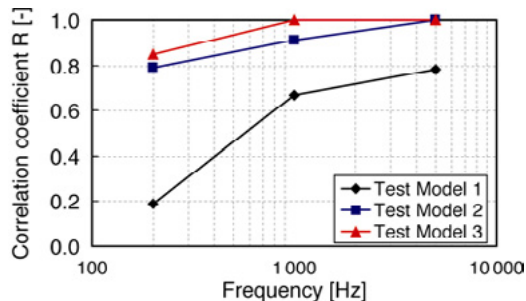


Fig. 14 Correlation coefficient (from Dpr housing to Interior cavity)

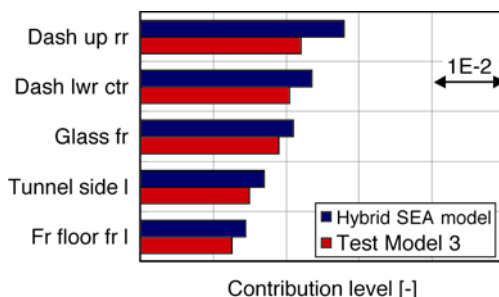


Fig. 15 Power contribution to interior cavity (after hybrid process)

5.2. Power Contributions to Interior Cavity Noise by Adjoining Subsystems

Figure 17 illustrates the power contributions of various adjoining subsystems to interior cavity noise, according to the Hybrid SEA model.

They indicate that the structural subsystems of the rear wheel house, floor, dashboard and tunnel are dominant in the 200 – 500 Hz band. Leaks from around the doors and door windows and the acoustic radiation from the front windshield dominate above 2 kHz. Thus, the analytical results gained from the use of this method will allow efficient decision-making about specifications for the reduction of road noise.

6. Conclusion

A method for creating a Hybrid SEA model has been proposed. The model is capable of predicting structurally-propagated road noise in the 200 – 5000 Hz frequency range with an accuracy of ± 3 dB and reproduces power flows among subsystems. Use of the Hybrid SEA model

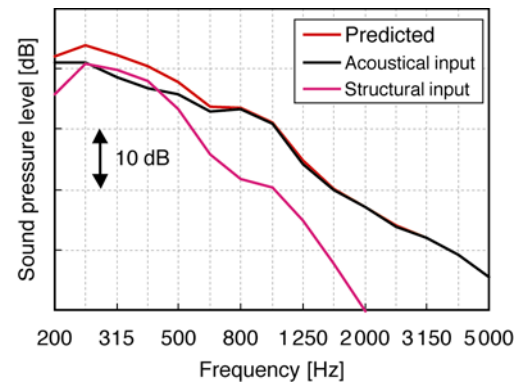


Fig. 16 Contribution to interior cavity sound pressure level

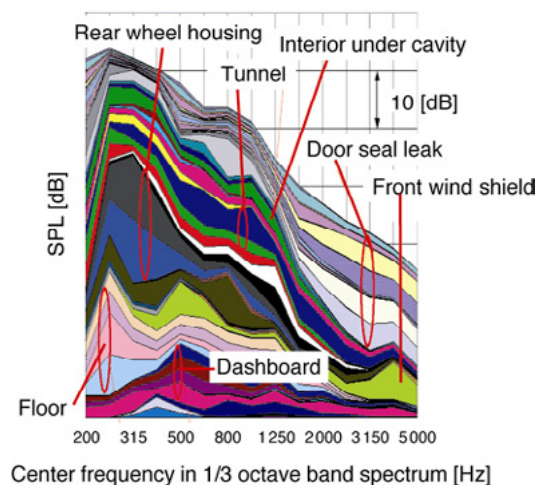


Fig. 17 Power contribution to interior cavity sound pressure level

constructed under this method enabled structural noise propagations to be distinguished from air-borne propagations. Also obtained was the contribution of noise passing through acoustic systems as well as the contribution of acoustically radiated noise to the interior cavity. Therefore, the model is expected to streamline the process of counter measuring road and other noise.

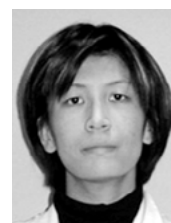
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