A study on the acoustic cavity model of vehicle interior cabins for accuracy enhancement based on modal and FRF correlation

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ABSTRACT
In vehicle noise simulation, the sound pressure is obtained from the acoustic cavity model coupled with the body structure. Therefore, the acoustic cavity model for the interior cabin of a vehicle is one of the most crucial factors to determine the accuracy of noise simulation. In this study, a series of tests to characterize the acoustic cavity is carried out and compared with the corresponding simulations. First of all, acoustic EMA (Experimental Modal Analysis) with multiple-excitation sources was carried out to obtain reference data. Exact acoustic cavity modes in interior cabins were identified by excitations with 6~12 loudspeakers. Then, modal and FRF correlation were investigated using experiment and simulation results. Frequencies, mode shapes and tendency of ATF (Acoustic Transfer Function) in the acoustic cavity were analyzed. In addition, HIF (Hyundai Index for FRF) was employed to quantify the degree of correlation among a large number of FRF comparison. Acoustic connections and equivalent heavy-air properties were applied in the interior cabin model to enhance the accuracy. As a result, the acoustic cavity model has been modified to achieve improved accuracy in modal and FRF correlation.

Keywords: Acoustic Cavity, Interior Cabin, Correlation, I-INCE Classification of Subjects Number(s): 75.3

1. INTRODUCTION
The noise analyses based on FE (finite element) models have been widely carried out in the initial stage of vehicle development. Furthermore, prediction of NVH performance using full-vehicle FE-models has been established as a general process in the automotive industry, since the contribution of vehicle simulation to the industry increases. This process has a great advantage to improve performance, and reduce weight & costs. Also, various design studies regarding booming and road noise of vehicles are available before testing vehicles. Therefore, accuracy of simulation in the vehicle development process has become more important recently.

\[ P = \sum_{i=1}^{m} \sum_{j=1}^{n} ATF_j \times Area_j \times VTF_i \times F_i \] (1)

As shown in Figure 1, a vehicle model for NVH analysis is categorized into two major parts: a structure part and an acoustic cavity part. The structure part which includes a trimmed body, a chassis and a power train has the information of VTF (Vibration Transfer Function, \( v/F \)) in the vehicle model. Also, the acoustic cavity which models the air in a vehicle interior cabin has the information of ATF (Acoustic Transfer Function, \( p/\dot{Q} \)). Where \( Area_j \) is expressed in the unit area of the surface coupled between the structure part and the acoustic cavity, the vehicle interior noise \( P \) is
Therefore, to enhance the accuracy of the total response in the vehicle simulation model, the reliability of each transfer function should be persistently improved. Especially, the acoustic cavity which composes the path from vehicle interior panels to the ear point of passenger has a significant effect on the result with respect to the modeling methods. For that reason, many automotive companies have conducted various studies on the acoustic cavity modeling to enhance accuracy for the noise analysis in the low frequency range. (1,2,3,4)

In this research, the first step in accuracy improvement of the acoustic cavity model is to obtain reliable results of experiment which can be compared to those of simulation. However, since the acoustic cavity in the vehicle interior cabin is a highly damped system due to interior trims, the accurate modal extraction for the acoustic cavity from testing is one of the most difficult challenges. Therefore, acoustic EMA (Experimental Modal Analysis) with multi-excitation sources was carried out to obtain reliable test results. Also, the suitable acoustic EMA methodology for vehicle interior cabin was studied.

In the second step, correlation between test and simulation results has been performed. Frequencies, mode shapes and tendency of FRFs were considered to enhance the accuracy of the simulation model. Basically, MAC (Modal Assurance Criteria) was used for objective comparison of mode shapes. In addition, HIF (Hyundai Index on FRF) was employed to quantify the degree of correlation among a large number of FRFs comparisons.

And, the final step was model updating. Acoustic connections and equivalent air properties were applied in the interior cabin model. Through these modifications, the acoustic cavity model was updated achieving improved accuracy in modal and FRF correlation.

![Vehicle Simulation Model](image)

Figure 1 – The vehicle simulation model for NVH analysis

2. EXPERIMENT

2.1 Theoretical Equation of Acoustic Modes

Theoretically, natural frequency and mode shape of a simple closed rectangular volume are represented as Equation (2) and (3). (5)

\[
f_{ijk} = \frac{c}{2\pi} \sqrt{\left(\frac{i}{L_x}\right)^2 + \left(\frac{j}{L_y}\right)^2 + \left(\frac{k}{L_z}\right)^2}
\]

\[
\Psi_{ijk} = \cos \frac{i\pi x}{L_x} \cos \frac{i\pi y}{L_y} \cos \frac{i\pi z}{L_z}
\]

However, the acoustic cavity of the vehicle interior cabin actually shows complicated characteristics. First of all, unlike structural EMA, modal peaks of the acoustic cavity don’t appear distinctly. And, it is difficult to extract exact mode shapes in the acoustic EMA because the acoustic
cavity is a highly damped condition due to interior trim parts. Also, the acoustic cavity is more complex in sedan type passenger vehicles because it is divided into two major parts: the main cabin cavity and the trunk cavity which becomes a kind of Helmholtz resonators. Moreover, since both of acoustic modes and vibro-acoustic coupled modes are extracted in a jumble in actual experiments, it is difficult to identify real acoustic modes to be compared with simulation results. Thus, multiple-excitations and detailed modal analysis procedures are needed to extract exact mode shapes. (6,7)

2.2 Test Set-up

A mid-size passenger vehicle was selected for acoustic EMA. Prior to actual experiments, a preliminary test was carried out to check linearity, repeatability, reciprocity, coherence, and loudspeakers. Maximum 12 Siemens (LMS) Q-Sources: Q_{mm} and Q_{nd} were used as loudspeakers in this modal testing. The locations of loudspeakers are presented in Figure 2. In addition, the array constructed using about 500 microphones was applied to measure the signal from loudspeakers as shown in Figure 3 for the modal correlation.

And, ATFs testing was performed for FRF correlation. Total 28 ATFs from driver’s and passenger’s ear points to main panels in the interior cabin were measured as can be seen in Figure 4, and they have been intensively managed in FRF correlation.

Figure 2 – Type and location of loudspeakers (Q-Source)

Figure 3 – The micro-phone array in the vehicle interior cabin

Figure 4 – ATFs testing for FRF correlation
2.3 Acoustic EMA (Experimental Modal Analysis)

Complexity of the system was extremely increased due to a high damping in the vehicle interior cabin and multiple excitations condition in acoustic EMA. Therefore, careful approach was required to extract correct acoustic modes. First, it was necessary to identify the existence of cavity modes with a small number of excitations. Then, exact modes should be extracted using modal indicator functions such as MMIF and CMIF after increasing the number of excitations. After modal extraction, the orthogonal characteristics of modes were checked with AutoMAC analysis. Also, the comparison between measured FRF and synthesized FRF was carried out to assure the quality of extracted mode shapes. As shown in Figure 5, acceptable results have been obtained in AutoMAC analysis and FRFs comparison.

At this stage, structure-coupled modes are mixed with acoustic cavity modes in modal testing results and need to be removed from the acoustic modal correlation between test and simulation. For this purpose, point mobility testing for structure panels was conducted to identify structure-coupled modes.

Finally, acoustic cavity modes in Figure 6 were extracted from acoustic EMA using multiple loudspeaker-excitations and experimental results with high reliability were obtained. The quality of mode shapes which were extracted from this multiple-excitation acoustic EMA were acceptable for the use in modal correlation. (8)

![AutoMAC](image1)

![Measured FRF vs Synthesis FRF](image2)

**Figure 5 – Evaluation of the acoustic EMA**

![Trunk mode](image3)

![Cabin F/A 1st mode](image4)

![Cabin L mode](image5)

![Cabin F/A 2nd mode](image6)

![Trunk L mode](image7)

![Cabin V mode](image8)

**Figure 6 – Acoustic mode shapes in the experiment**
3. CORRELATION

3.1 Validation of the Initial Simulation Model

A typical acoustic cavity model in the passenger vehicle is presented in Figure 2. Modal and FRF analyses for the initial simulation model were conducted using MSC/Nastran. And, results were compared to the previous modal testing results. Frequencies, mode shapes and FRFs were compared to validate the acoustic cavity model.

As shown in Table 1, modal frequencies obtained from simulation are similar to test results. But, frequencies of the trunk mode, fore & after mode and vertical mode have some deviation with experimental results, which need to be revised referred to experimental results.

<table>
<thead>
<tr>
<th>Experiments</th>
<th>The initial simulation model</th>
<th>Mode shape</th>
</tr>
</thead>
<tbody>
<tr>
<td>25.1</td>
<td>18.5</td>
<td>Trunk</td>
</tr>
<tr>
<td>71.8</td>
<td>77.2</td>
<td>Cabin F/A</td>
</tr>
<tr>
<td>95.3</td>
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<td>Cabin L</td>
</tr>
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<td>139.7</td>
<td>Cabin V</td>
</tr>
</tbody>
</table>

And, MAC (Modal Assurance Criteria) in Equation (4) was employed to validate mode shapes. Figure.7 shows MAC of the experimental and the initial simulation results. As shown in Figure.7, MAC below 100Hz is near to 1, which means mode shapes are almost same in the experimental and the simulation result. Therefore the initial simulation model shows similar modal characteristics compared to test modes below 100Hz. However, MAC of modes above 100Hz is less than 0.7. Especially, MAC of the vertical mode which has the important effect on the vehicle noise analysis is less than 0.7, which means the mode shape of the vertical mode in initial simulations does not have enough accuracy. Actually, the nodal line of the vertical mode is different with the test result like in Figure 9 and it is required to be revised.

\[
MAC(A, X) = \frac{||\{\psi_X^T\}^T \{\psi_A^T\}||^2}{\{\{\psi_X^T\}^T \{\psi_X\}\} \{\{\psi_A^T\}^T \{\psi_A\}\}}
\]

Figure 7 – MAC between the initial simulation model & the experimental result
In the next step, FRF based correlation was carried out. Tendency of FRFs between the experiment and the simulation was examined. In this case, the evaluation for similarity of two FRFs is required. But, the traditional index such as FRAC (Frequency Response Assurance Criterion) is not able to provide the proper evaluation that was accorded with the subjective rating of engineers. Therefore, HIF (Hyundai Index for FRF) in Equation (5) was employed. HIF based on probabilistic approach was developed by Lee & Kim to evaluate the similarity of two graphs. (9,10) It represents the degree of correlation as a number from 0 to 1 as MAC. HIF provides more practical and reasonable results than FRAC based on mathematical approach. Also, HIF is useful to quantify the degree of correlation among a large number of FRF comparisons.

\[
HIF = \frac{pdf_{N(\text{FRF}_{\text{CAE}}, \sigma^2, \text{dB})}(\text{FRF}_{\text{CAE}})}{pdf_{N(\text{FRF}_{\text{TEST}}, \sigma^2, \text{dB})}(\text{FRF}_{\text{TEST}})}(\omega)
\]  

(5)

FRF correlation results are shown in Figure 8. Some peak of ATFs in the initial simulation is appeared at the incorrect frequency because it is not completely correlated with the experiment. The amplitude of ATFs is over-estimated or under-estimated over the frequency range. And, some ATF path in the initial simulation result like the right graph in Figure 8 is under-estimated excessively.

Overall, The HIF average for 28 ATF paths in the interior cabin was 0.71 that is ordinary value as a model before the correlation. Also, this model is in line with typically applied vehicle development. However, more precise modal and ATF correlation are required to enhance accuracy of the vehicle noise analysis.

![Figure 8 – FRFs comparison (ATFs) for the initial simulation model](image)

### 3.2 Model Updating

As described in the previous experiment and study (8,11), the cockpit module which is located at the front of the main cavity and the rear package tray which connects the main cavity & the trunk have carried out an important key-role in the acoustic cavity of the vehicle interior cabin. Therefore, new modeling technique should be applied to enhance the accuracy of the acoustic cavity model. Also, there is a demand for proper balance in detail description, robustness and modeling convenience when considering a new modeling technique.

First of all, the equivalent material property with heavy-air characteristics was applied in the cockpit module section. It affects the frequency of the 1\textsuperscript{st} F/A mode which is one of the most important modes among acoustic cavity modes. Therefore, the F/A mode could be shifted to the lower frequency according to the experimental result.

Also, because this treatment affected the acoustic characteristics, mode shapes of the 2\textsuperscript{nd} F/A and the 1\textsuperscript{st} vertical mode have been changed as a result of the acoustic EMA. Figure 9 shows the mode shape of the 1\textsuperscript{st} vertical mode, which is generally related to the booming noise in driving condition. But, the nodal line of the initial simulation was not correct, and the mode shape is different as compared with the experimental result. This difference causes inaccuracy of ATFs in the acoustic cavity and noise responses of the vehicle NVH analysis. However, the nodal line has been improved according to the experimental result in the final improved simulation. Therefore, the mode shape of the 1\textsuperscript{st} vertical mode in the final simulation model has become more similar to the experimental result.
Secondly, the rear package tray modeling has been modified to enhance the accuracy. Holes on the rear package tray panel in Figure 10 were considered in detail with solid elements and MPC (Multipoint Constraint Set Selection), which are called acoustic connections in this paper. These holes have contributed a significant effect on the acoustic characteristics in the cabin. And, the acoustic connection has not only the same effect with detailed holes modeling but also an advantage to reduce modeling time.

Therefore, an automated modeling tool for the acoustic connection has been developed to save modeling time and it has applied to the pre-processor of the finite element analysis. Also, the rear package trims which have the equivalent material property and the air under the trim panel were considered as shown in Figure 10. These modifications have provided enhancement accuracy in the frequency of the trunk mode and the amplitude of ATFs in the rear side of the cavity.

Table 2 and Figure 11 show the modal correlation of the final improved simulation model compared to the experimental results. Accuracy of the frequency and mode shape in the final model was remarkably enhanced. The modal correlation of the trunk mode, the 1st F/A mode and the 1st vertical mode of the acoustic cavity is improved. Especially, MAC of the 1st vertical mode increased significantly from 0.61 to 0.83. Figure 12 shows the mode shapes of the final simulation model.

Furthermore, FRF correlation for ATFs in the acoustic cavity was enhanced as shown in Figure 13. Since accuracy of modal frequencies was improved, the location of peaks in FRFs shifted to more precise position. Also, tendency and level of ATFs have been improved as shown in Figure 13 because modified modeling technique for the cockpit module and the rear package tray were applied in the final simulation model. And, Figure 14 shows HIF between the initial and the final model. As shown in Figure 14, HIF values have been totally improved. Average HIF value has been increased from 0.71 in the initial model to 0.80 in the final model.

Finally, NTFs (Noise Transfer Function, a/Q) were examined for verification of the final simulation model which was improved for ATFs. NTFs from the driver’s and passenger’s ear-points to the panels surrounding the acoustic cavity were measured. And, it was compared to the simulation results. As a result, NTFs in the final improved simulation model were significantly enhanced in Figure 15. Therefore, accuracy of the vehicle noise analysis can be increased with this new modeling technique of the acoustic cavity in the interior cabin.

Figure 10 – The rear package tray panel and trim

Figure 9 – Mode shapes of the 1st vertical mode of the acoustic cavity
Table 2 – Modal frequency of test result & simulation model [Hz]

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Figure 11 – MAC between the final improved simulation & the experimental result

Figure 12 – Acoustic mode shapes in the final simulation

Figure 13 – FRF correlation (ATFs) after model updating
4. CONCLUSIONS

A study on the acoustic cavity of the vehicle interior cabin for correlation enhancement to improve accuracy of the vehicle noise analysis was carried out. Acoustic characteristics including mode shapes and frequencies of the cabin were studied with detailed acoustic EMA and ATFs test. Also, it was confirmed that reliable mode shape for modal correlation can be extracted from acoustic EMA using multiple excitations. And, modal and FRF correlation have been conducted based on these experimental results. Frequencies, mode shapes, ATFs and NTFs in the simulation model were compared to the experimental results with correlation index like MAC and HIF. As a result, accuracy of the final simulation model was significantly enhanced using treatments of equivalent material property and acoustic connections in the cockpit module and the rear package tray. Furthermore, improved modeling technique for the acoustic cavity in the vehicle interior cabin has been established through this research. Finally, accuracy of the vehicle noise analysis can be increased using this improved acoustic cavity model.

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