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Advanced Noise Prediction and Cabin Sound Optimization in BEV Using Hybrid SEA Model

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ABSTRACT: The rise of BEV has highlighted high-frequency motor and gearbox noise, creating new challenges for automotive noise prediction. Current simulation methods struggle with high-frequency noise predictions. Hybrid statistical energy analysis (HSEA), which combines analytical and experimental methods, enables more accurate noise prediction and assessment of vehicle design modifications, particularly for cabin noise. This paper demonstrates the effectiveness of HSEA, especially when addressing noise caused by acoustically sensitive structural transfer paths, and its improvement potential for vehicle development efficiency.

KEY WORDS: Battery Electric Vehicle, Noise and Vibration, Motor Noise, Cabin Noise, Structure Borne Noise, CAE, FEM, SEA

1. INTRODUCTION

The rise of Battery Electric Vehicles (BEV) is transforming the automotive landscape. Drivers and passengers expect that BEV vehicles will be quieter than fuel-powered vehicles due to the absence of internal combustion engine (ICE) noise. However, noises from other sources like actuators, pumps, or electric drivetrain become more noticeable due to the lack of ICE noise. The prominence of such noises can negatively impact the perceived sound quality of the vehicle.

Noise from BEV powertrains can also become a problem due to the lack of ICE noise. The motor creates noise and vibration due to the time-varying electromagnetic forces within the motor during operation. Gear noise and vibration is a result of the forces created by imperfect motion between mating gears. Motor and gear noise are order based noises that will vary in frequency as the operating speed of the components changes. Both sources create a tonal noise that will stand out against other broadband noises in a vehicle, such as those caused by wind or road surfaces.

As the automotive industry is demanding shorter times to market, the need for accurate simulation and other virtual verification methods is growing. Conventional computer-aided engineering (CAE) methods for Noise and Vibration (NV) are often limited to frequencies at 500Hz or below, which is inadequate for BEV powertrain noise analysis due to the high-speed operation of motors and gearboxes. Predicting high frequency powertrain noise - particularly in the cabin of the vehicle - is a challenge that requires virtual solutions to support accelerated automotive development timelines [1-5]

2. ACCURATE POWERTRAIN NOISE PREDICTION

The NV development of a new automobile typically undergoes several stages, with each stage consisting of various prototype vehicles and testing. As the development of the vehicle progresses, limitations due to cost and weight can force NV engineers to adjust and re-work their plans. Component design changes for strength, durability, or even noise countermeasures can complicate the estimation of powertrain noise in the cabin, and it is almost impossible to verify every possible impact by physical test. Additionally, shortened development timelines may reduce the availability of prototypes, furthering the need for vehicle sound predictions without the need for vehicle testing. To expedite the evaluation and design judgment within a reasonable timeline, a CAE method to predict the cabin noise is desired.

CAE methods exist for calculating the response characteristics of individual parts or systems, but the prediction of cabin noise that will be experienced by a customer is more challenging. Conventional CAE [Finite Element Method (FEM)] is computed based on a modal analysis and it can be often adequate at lower frequencies where each mode can be clearly separated. Correlation of the experiment and model becomes more difficult above 500Hz because a large number of overlapping modes may exist. Statistical Energy Analysis (SEA) calculates phenomenon based on energy, using statistical averaging method in subsystems which are the smallest units in SEA. This method can be used in situations where many overlapping modes exist, and it has been effectively used for higher frequency analyses. The SEA technology utilized in this paper is described in detail in Chapter 3. [6-10]

A common vibration transfer path for unwanted powertrain noise encountered in vehicle development is the powertrain mounting system. Powertrain mounts have strong interactions with other functional areas such as handling, crash safety, and durability. Achieving a balanced design for these functions requires optimization studies, and there is risk of re-design if failures occur during the testing of the components. Powertrain noises perceived by passengers can be significantly impacted by such modifications, so it is strongly desired a predictive tool to accurately assess the impact of any changes without the need for an actual test. In this paper, the establishment of installing a powertrain mount model into an entire vehicle SEA model and the application for estimating order-based noise are discussed.

3. ADVANCED HSEA APPLICATION

3.1. What is HSEA?

SEA theory treats the NV as power flow between subsystems in equilibrium conditions. It can accurately describe high frequency phenomena because it is built on the assumption that each subsystem uniformly vibrates. In other words, it can effectively work when many overlapping modes exist in a system. An entire vehicle can be easily simulated because the number of elements (or subsystems in SEA) is significantly lower than a FEM model. Therefore, SEA is simpler model than FEM for investigating high frequency performance of the entire vehicle.

A Hybrid SEA (HSEA) technology was established to be applied to real world industries such as automotive. It is a hybrid of analytical and experimental SEA models, and it has been successful in supporting effective development processes and shortened development timelines.

Analytical SEA

An analytical SEA model is completely theoretical and is built based on the vehicle construction information and Equations 1 and 2.

$$\eta_{\mathrm{CLF}} = \frac{cS}{4\omega V}\tau \text{ [Equation 1]}$$

$$\eta_{\mathrm{DLF}} = \frac{cS}{4\omega V}\alpha \text{ [Equation 2]}$$

η_{CLF} Coupling Loss Factor (Amplitude of power transmission between subsystems)

η_{DLF} Damping Loss Factor (Amplitude of power dissipation inside a subsystem)

τ Transmission coefficient (Calculated from car construction information)

α Absorption coefficient (Calculated from car construction information)

S Surface area of subsystem [m^2]

c Sound speed [m/s]

V Subsystem volume [m^3]

Vehicle construction information, such as the body panel material and thickness, soundproofing material specifications and coverage area, etc., is utilized to calculate τ and α. Then, the SEA parameters η_{CLF} and η_{DLF} can be calculated. The analytical SEA model establishes local relationships between contiguous subsystems using vehicle drawing specification, which allows for the estimation of design change impacts by modifying each individual component's specifications.

Experimental SEA

An experimental SEA model is created by conducting a vehicle test, utilizing a large number of accelerometers and microphones. The power transfer between subsystems and the energy dissipation within each subsystem are measured using speaker and hammer excitation methods. At least two microphones or accelerometers are located in each subsystem to measure the response. An example of the sensor installation on a vehicle is shown in Figure 1, and an example of the quantity of subsystems and sensors required for creating an experimental HSEA model are listed in Table 1.

Figure 1: Test Vehicle with Sensors Applied

	# of subsystems	# of sensors
Acoustic (Exterior)	**40**	**92**
Acoustic (Interior)	**20**	**70**
Structure	**200**	**260**

Table 1: Summary of the Subsystems and Sensors required for Experimental SEA Model Creation (Example)

The experimental SEA can describe realistic phenomena because the SEA parameters η_{CLF} and η_{DLF} are tuned to describe the measured data. Therefore, experimental SEA models can accurately estimate power flows and contributions using measured input powers, such as the powertrain noise and vibration during vehicle acceleration. However, it does not have the capability for verifying the impacts of design modifications by itself.

3.2. HSEA Capability

The HSEA model offers engineers the capability to investigate realistic phenomena and the impacts of design modifications to those phenomena. The HSEA model is an extremely accurate representation of an entire vehicle that can predict sound pressure level, power contribution, and power flows ranging from 0.1kHz - 10kHz. Compared to a conventional phase-referenced contribution analysis, which is experimentally modeled including phase and direction information, the HSEA model can analyze to a higher and wider frequency range because the NV phenomena are treated using energy scaling while phase-reference analysis is often limited to 10Hz - 500Hz.

The accurate prediction of cabin noise after design changes is another capability of HSEA. It is possible because the analytical and experimental SEA models can be correlated using Equation 3 with SEA parameter (η).

$$\eta_{Mod}^{\text{Experimental SEA}} = \eta_{\text{Base}}^{\text{Experimental SEA}} \times \frac{\eta_{\text{Mod}}^{\text{Analytical SEA}}}{\eta_{\text{Base}}^{\text{Analytical SEA}}}$$

[Equation 3]

It is assumed that the ratio of base and modified conditions in the analytical SEA model is the same as in the experimental SEA model. This modification effect is verified during the model creation by comparing the actual experiments to the HSEA prediction.

HSEA has been successfully applied for many test modes such as road noise and engine noise. [11-21] An example of the HSEA prediction for a next generation vehicle development is shown in Figure 2. The effect of component modifications such as floor carpet, insulators, etc., was predicted using Equation 3. The performance of the next generation vehicle as a whole can be estimated.

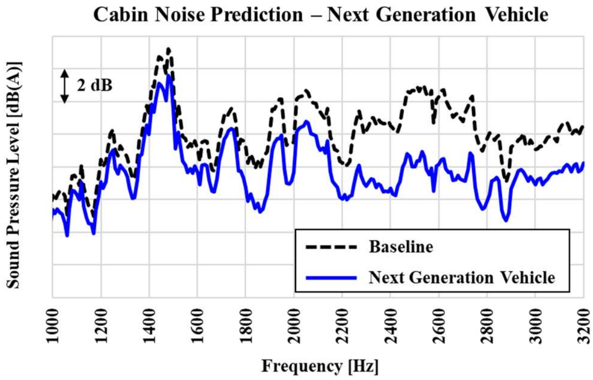

Figure 2: Example HSEA Cabin Noise Prediction for New Vehicle Model

3.3. Advanced HSEA Including Mount Modeling

One limitation of the conventional HSEA model is a difficulty in analyzing upstream power flows, such as those through the powertrain mounting system. A highly accurate experiment is required to construct the experimental SEA model. The signal to noise ratio of measurement worsens due to attenuation from the mount isolation bushings, which restricts the capability for the model to make predictions in these areas.

For example, conventional HSEA models have the ability to indicate that subframe vibration is dominant contribution source of powertrain noise during acceleration, but it cannot identify the contribution levels of each mount to the subframe vibration. In order to expand the HSEA capability, modal hammer experiments are conducted to characterize the mount system behavior. When the powertrain mount behavior is added to the HSEA model, we obtain the advanced HSEA model described in this paper.

A powertrain can be connected to a vehicle body of subframe using several mounts, which include the isolation bushings. Each mount can be modeled using four measurement locations, defined as seen in Figure 3:

A. The mount attachment points to the powertrain
B. The active side of the mount isolation bushing
C. The passive side of the mount isolation bushing
D. The mount attachment points on the subframe or body

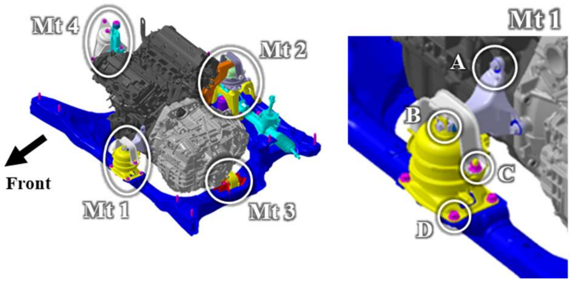

Figure 3: Powertrain Mount Modeling

Each point of A, B, C, or D may have several attachment points, and accelerometers are attached to each point. The transfer functions between points are measured, and transfer functions in energy scale are defined as a mount model after averaging directions (X, Y, Z) and attachments in each point. Vibration at the A points during actual driving conditions are also measured, and they are transferred to the input of the HSEA model using the transfer functions of the mount model. The total power input into the subframe from the powertrain (A points) through the mount system can be calculated by the summation of power flows from each mount using Equation 4.

$$\text{Power Input}^{\text{Total}} = \sum_i \text{Vibration at } \mathrm{A_i} \text{ point} \times \mathrm{TF}_i^{\mathrm{A}\rightarrow\text{Subframe}} \quad \text{[Equation 4]}$$

Identification of Structurally Sensitive Mounts

The one of benefits of the HSEA model is an ability to identify structurally sensitive mounts using the power flow and contribution analyses. The advanced HSEA model enables the separation of power inputs into the subframe through the mounts during driving conditions. This capability to find the sensitive structural transfer paths is expanded compared to the conventional HSEA model, as shown in Figure 4. As a result, sensitive transfer paths can be identified quickly and easily.

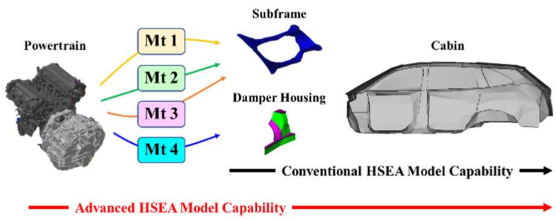

Figure 4: Comparison of the Conventional and Advanced HSEA Model Capabilities

Prediction of Cabin Noise Impacts due to Mount Modification

The effect of mount modifications to cabin noise can be predicted by incorporating an FEM analysis. FEM can help to identify the dominant modes in a structure and to evaluate the structural modifications to shift modal frequency. In this paper, the transfer functions of the baseline and modified mount specification are calculated by FEM. Then, modification is applied to the transfer function of the advanced HSEA as shown by Equation 5.

$$TF_{\text{Mod}}^{\text{Advanced HSEA}} = TF_{\text{Base}}^{\text{Advanced HSEA}} \times \frac{TF_{\text{Mod}}^{\text{FEM}}}{TF_{\text{Base}}^{\text{FEM}}} \quad \text{[Equation 5]}$$

The concept of Equation 5 is the same as Equation 3 for predicting the impacts of design modification. The difference is that while the base mount model is determined by the experimental HSEA model, the transfer function modification effect is calculated by an FEM analysis.

By combining Equation 4 and 5, changes to the power input from the powertrain to the subframe due to the mount modification can be calculated. Therefore, the effect of mount modifications to cabin noise can be predicted for various driving conditions.

4. CASE STUDY

In this chapter, the usefulness and significance of advanced HSEA are proven by the analysis of the order-based noise shown in Figure 5. This order-based noise stands out among the relatively faint sound levels surrounding it, and there is a risk of a negative feeling for the customers due to the perception of this undesirable noise.

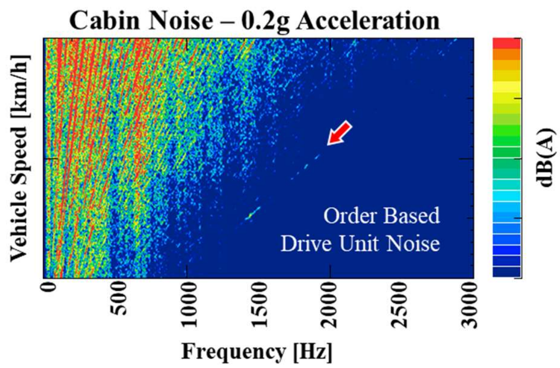

Figure 5: Order Based Noise During Acceleration

4.1. Clarification of the Significant Noise Source

The input contribution analysis is the most powerful tool in the HSEA model for identifying the dominant power paths impacting cabin noise in a given driving mode. A comparison of the input contribution between conventional HSEA and advanced HSEA are shown in Figure 6. Conventional HSEA shows that the

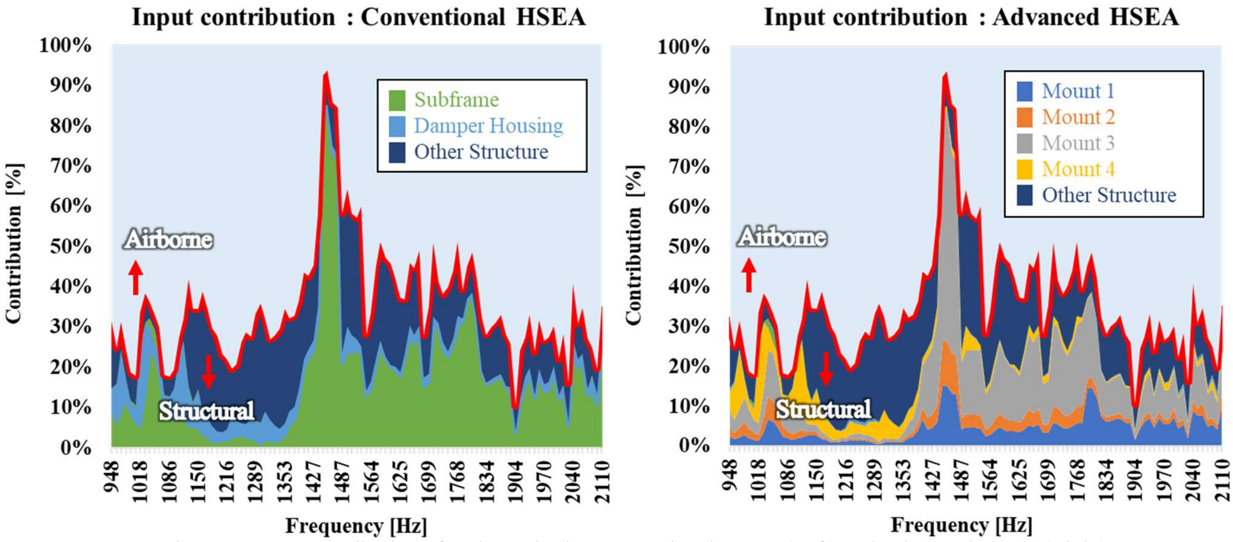

Figure 6: Input Contribution of Order Noise by Conventional HSEA (Left) and Advanced HSEA (Right)
Airborne/Structural contributions are indicated in the area above or below the red line, respectively.

subframe vibration causes 80% of cabin noise in the frequency near 1500Hz, while it shows that only 30-40% is caused by the subframe vibration at other frequencies. Additional investigation would be required to identify the mount with highest contribution to the subframe vibration. On the other hand, advanced HSEA can clearly show that cabin noise is significantly affected by the power input through mount 3.

4.2. Prediction of Cabin Noise with Mount Modification

Based on the indication of advanced HSEA analysis as shown in Figure 6, FEM found that the inertance of the mount 3 bracket is large near 1500Hz, as shown as black line in Figure 7. Addition of a mass damper to the mount bracket was proposed as shown in Figure 8 to improve the inertance characteristic at this frequency while minimizing the potential for negative impacts to other functional areas, such as durability or safety. The weight of the mass damper was tuned to target vibration improvement at 1500Hz as shown by the blue line in Figure 7. The validity of the FEM model can be confirmed by comparing the inertance at the bracket tip of the baseline and the countermeasure. The comparison of the FEM and experimental results are shown in Figure 7.

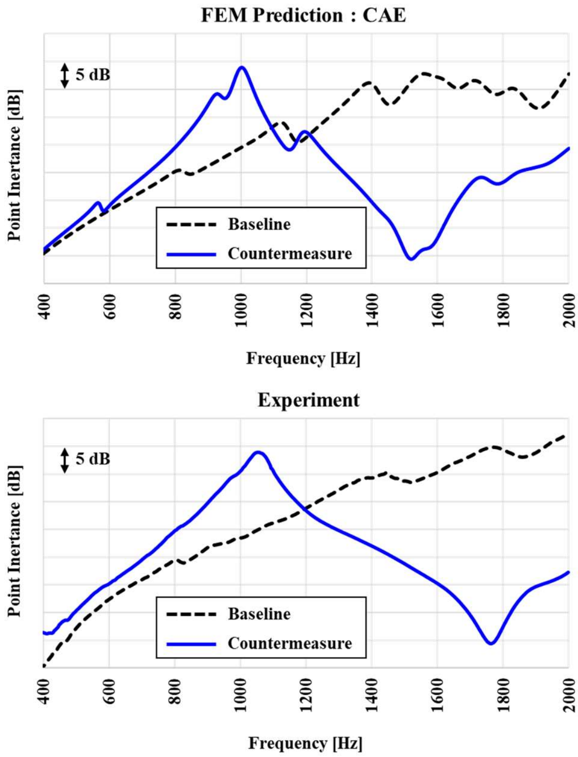

Figure 7: Mount Bracket Tip Inertance
(Top) CAE Calculation, (Bottom) Experiment

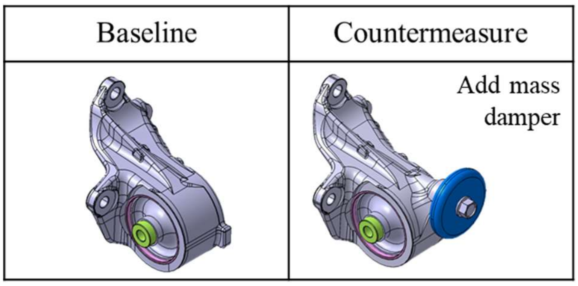

Figure 8: Mass Damper for Bracket

The transfer function modification, which is the ratio of transfer functions (A-Point to D-Point, Mount 3) between baseline and countermeasure mount brackets, is calculated by FEM as shown in Figure 9. It can be seen that the amplitude of the transfer function near 1500 Hz is reduced, as expected. The amplitude increases near 600Hz, but this was not of concern based on the input power levels from the powertrain at that frequency.

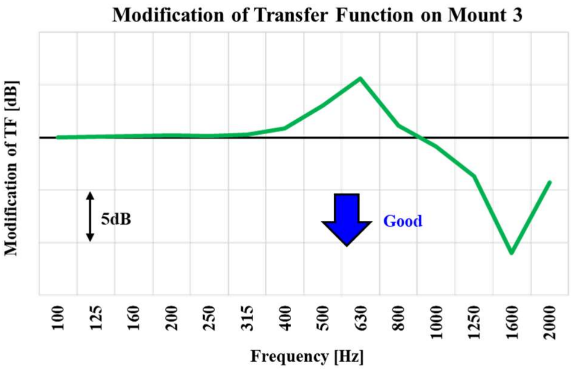

Figure 9: Modification of the Transfer Function
(A-Point to D-Point, Mount 3)

The power input of the powertrain to the subframe is calculated in the advanced HSEA model based on Equation 4 and 5, using the calculated transfer function for mount 3. In SEA, the power balance equation in a subsystem is written by Equation 6.

$$\Pi = \omega \eta_{\mathrm{TDLF}} E \text{ [Equation 6]}$$

Π Inflow Power into a subsystem

η_{TDLF} Total Damping Loss Factor (Total amplitude of power dissipation from a subsystem (DLF + CLF))

ω Angular frequency [rad / s]

E Energy in a subsystem ($= 10\log(mv^2)$) [J]

m Mass of subsystem [kg]

v Vibration velocity of subsystem [m/s]

The modified inflow power into subframe was also calculated using Equation 4 and 5 and the energy of the subframe is predicted as shown in Figure 10. As expected, the energy inflow to the subframe is reduced by approximately 10 dB in the frequency range surrounding 1500Hz.

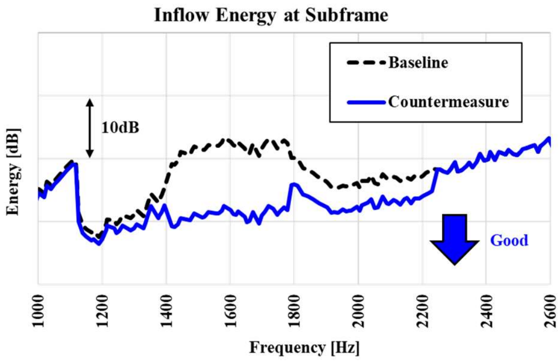

Figure 10: Inflow Energy to the Subframe During 0.2g Acceleration

Finally, the effect of mount 3 modification on cabin noise is calculated by advanced HSEA as shown in Figure 11. The cabin noise is reduced by approximately 7dB at 1500Hz. The CAE prediction was compared with experiment, and the accuracy of the advanced HSEA model was verified. Establishment of this new technology allows accurate predictions of cabin motor and gear noise without the need for a complete vehicle test. The lack of need for additional testing is a great advantage of advanced HSEA when compared to conventional CAE methods.

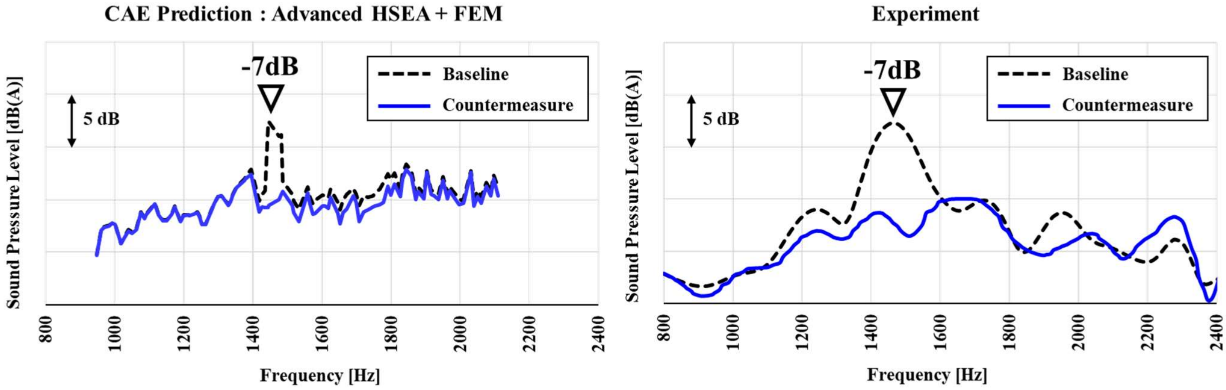

Figure 11: CAE Estimation and Experiment of Order Noise during Acceleration

5. CONCLUSION AND FUTURE PLANS

The current automotive industry situation is becoming more challenging due to the requirements of shorter development terms and fewer prototypes. NV development of BEV requires investigation of a wide frequency range (above 500 Hz). Accurate prediction of high frequency NV phenomena, especially the noise in the cabin of the vehicle, is desired to support accelerated automotive development timelines and lower costs of test-less development.

In this paper, the advanced HSEA model combining the powertrain mount models and the conventional HSEA model has been established. It can identify the dominant power paths contributing to cabin noise and identify structurally sensitive mounts. The impact of a proposed countermeasure by mount modification was accurately predicted by the combination of FEM and HSEA. This capability has potential to contribute to reduced development timelines and costs.

The impact of adding a mass damper to the powertrain mount was showing in this paper, but other modifications are also possible. For example, bracket shapes or bushing rubber characteristics can also be evaluated using the advanced HSEA model. This new technology is also useful to predict next generation vehicle performance based on component specification changes without the need for prototypes or testing.

Prediction of cabin noise by CAE is especially important because considerable time and cost can be spent verifying actual parts. Additionally, modifications to components are not implemented just for NV considerations, but also for areas such as durability and safety. These design changes must also be evaluated for their impact, and this technology provides the capability to evaluate the impact to powertrain noise without the need for actual parts testing.

The latest development process for generation vehicles using CAE without the need for actual vehicle testing is shown below.

1. Prediction of the cabin noise using updated advanced HSEA based on parts specifications or issued drawings
2. Judgment of the vehicle performance against targets that have been established for a given model
3. Weight or cost reduction measures if required based on vehicle targets
4. Countermeasure development for powertrain noise using the advanced HSEA method if the NV targets have not been achieved

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