Acoustic Packet Optimization of Tire Noise Based on SEA Method

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Abstract. As the size of the engine decreases and its performance increases, its noise also decreases, and tire noise has become an important source of vehicle noise. Based on the Statistical Energy Analysis (SEA) method, use Hypermesh and VA-One software to establish a SEA model; through the vehicle PBNR simulation analysis and test benchmarking, the analysis model was calibrated and the accuracy of the simulation analysis was improved. In this research, a new TPNR calculation method is proposed to evaluate the noise reduction effect of tire noise excitation to the car. The acoustic performance is evaluated based on the calibrated SEA analysis model by optimizing the thickness, leakage rate and coverage of the acoustic bag at the luggage compartment floor, front and rear floors, and front and rear wheel covers. It is found that the optimization scheme for the front and rear floors and the luggage compartment floor has better effect, but the optimization effect for the rear wheel cover is not obvious.

1. Introduction
Cars are excited by various sound sources when they are driving. Excitation sources include powertrain, intake and exhaust systems, tires contacting the road noise, etc. [1]. When the car is accelerating, the tire noise contributes 20\%-50\% to the noise inside the car; when the vehicle is in the cruising phase and the speed is as high as 80-100km/h, the tire noise contributes up to 80\%-100\% [2]. Therefore, the acoustic treatment of the airborne noise generated by tires is of great significance.

In the process of sound insulation and noise reduction of tire noise, factors such as the sound absorption performance, material combination and arrangement position of the sound insulation material body will directly affect the noise reduction effect [3]. The optimization design of acoustic package for tire noise control is of great significance.

This paper takes a passenger vehicle as the research object, based on its three-dimensional digital model and initial acoustic package design, and uses the SEA analysis method to establish a vehicle SEA simulation analysis model. This study conducted a basic analysis of the noise sound pressure level at the right ears of the driver and rear passengers of the basic vehicle under tire noise excitation, and compared it with the test, and calibrated the SEA analysis model. A TPNR calculation method is proposed to measure the noise reduction effect of the vehicle acoustic package on tire noise excitation. By optimizing the laying position and material ratio of the acoustic package on the important transmission path, the interior noise under the excitation of tire noise is significantly reduced.
2. SEA analysis method

2.1. SEA theory
 SEA is to divide a complex system into multiple sub-systems that are convenient for analysis based on statistics, and analyze the vibration energy transmission between each sub-system from an energy perspective, and give high-frequency noise and vibration problems. Provides a solution [4].

The SEA method is based on the energy exchange and balance between systems and follows the principle of energy (ie power flow) balance per unit time. Among them, in a complex system composed of N subsystems, the power flow analysis matrix form is as follows [5]:

\[
\begin{bmatrix}
\Pi_1 \\
\Pi_2 \\
\vdots \\
\Pi_N
\end{bmatrix} = \omega
\begin{bmatrix}
\eta_1 + \sum_{j=1}^{N-1} \eta_{1j} & -\eta_{12} & \ldots & -\eta_{1N} \\
-\eta_{21} & \eta_2 + \sum_{j=2}^{N-1} \eta_{2j} & \ldots & -\eta_{2N} \\
\vdots & \vdots & \ddots & \vdots \\
-\eta_{N1} & \ldots & \ldots & \eta_N + \sum_{j=N}^{N-1} \eta_{Nj}
\end{bmatrix}
\begin{bmatrix}
E_1 \\
E_2 \\
\vdots \\
E_N
\end{bmatrix}
\]

(1)

Where: \(\Pi_i\) is the input power of the i-th subsystem; \(E_i\) is the energy stored in the i subsystem; \(\eta_{ij}\) is the coupling loss factor between the i subsystem and the j subsystem; \(\omega\) is the center frequency of one-third octave band; \(\eta_i\) indicates the internal loss factor of the i subsystem. As long as the input and output power and loss factor are given, the system energy can be obtained, and the sound pressure level of each subsystem can be further obtained.

3. SEA full-vehicle model

Based on the finite element model of a certain vehicle interior car body, the SEA model of the full vehicle is established. Based on the principle of sub-system modal similarity [6], the structure is based on the physical characteristics of the structure (material, thickness, etc.), the geometric characteristics of the structure, the flat plate (such as the front wall, the floor), and the single curvature plate (such as the door, ABC column). The main principle of subsystem division is to divide the full vehicle into 614 structural subsystems. According to the distinction between left and right, the front row, rear row and trunk area, the head, waist and leg areas are the main principles for the definition of acoustic cavity subsystems. The interior and exterior of the car body are divided into 40 acoustic cavity subsystems. By generating 1079 surface connections between the acoustic cavities in the car and between the acoustic cavities outside the car, the energy exchange between the various subsystems is realized, and the physical properties and parameters of each subsystem are defined [7]. The theoretical formula is used to calculate the modal density of each subsystem in the power flow balance matrix, the internal loss factor and the coupling loss factor between the subsystems. The SEA model of the vehicle and the schematic diagram of the division of each subsystem are shown in Figure 1 and Figure 2.

Fig 1. The structural subsystem and the internal and external acoustic cavity subsystem
Fig 2. The face connection between subsystems

Using the original acoustic package of the sample car, establish the cabin cover insulation pad, rear motor insulation pad, front wall inside and outside, carpet, rear wheel cover, trunk carpet and other acoustic package structures in the SEA model of the vehicle, and conduct model quality inspection. The SEA model of the vehicle is calibrated by leaking loading, increasing the transmission loss of the via hole at the front wall, increasing the sound-absorbing layer of the center console, and correcting the surface area and circumference of the sound cavity inside and outside the vehicle.

4. Full-Vehicle model benchmarking

4.1. PBNR test
The traditional noise reduction (NR) test has high requirements for the test environment, and the external environmental pressure needs to be used as a reference for the next iteration test, resulting in the lack of repeatability of this method and low accuracy of the results [8]. Power Based Nosie Reduction (PBNR) test has many advantages compared to traditional NR test, such as reciprocity, good repeatability, high accuracy, and can be used for vehicle-level and subsystem-level SEA Model verification [9].

The energy-based sound insulation test is carried out in the semi-anechoic chamber of the whole vehicle, and the engine of the prototype is turned off and placed on the rotating hub to measure the sound insulation performance of the vehicle body to the sound source excitation. During the test, the doors and windows of the cab were kept in a closed state. Using reciprocity, the response points outside the vehicle were arranged in four areas: engine compartment, left front tire, left rear tire, and front floor. The volume sound source is placed inside the vehicle body, and the front row sound source is located at the driver's right ear, and white noise source excitation is applied. In the rear row, volumetric sound sources are arranged on the left right ear of the rear row, the left waist of the rear row, the left leg of the rear row, the right waist of the rear row, the right leg of the rear row, the upper part of the trunk and the lower part of the trunk respectively. Apply white noise source excitation and average the results.

In order to reduce random errors, microphones are arranged in three directions in each sound field area for measurement, and the measured values are averaged as the test result of the working condition. Use the LMS Test. Lab test system to collect and record the sound pressure signal of each measuring point, process the test data with a frequency range of 250-10000 Hz, and perform 1/3 octave frequency analysis. Calculate the difference between the sound pressure signal of each measuring point outside the vehicle and the sound source signal of the excitation point, The average sound insulation curve of each measuring point when the sound source is excited by the driver's right ear and the average sound insulation curve of each measuring point when the rear passengers are excited after the average processing are obtained.

4.2. SEA analysis and test benchmarking
In the vehicle SEA model, a 1W sound source excitation is applied to the driver's right ear and the middle of the rear row, and the sound insulation curve from each excitation point to each measurement point corresponding to the test is obtained by simulation calculation, and the test results are compared. Under the excitation of the driver's right ear sound source, the PBNR curves obtained by the test and
simulation analysis corresponding to the four areas of the test engine compartment, left front tire, left rear tire, and front floor are shown in the figure.

It can be seen from Figures 3-4 that the frequency range has good consistency under the excitation of the driver’s right ear and the middle of the rear row, and the absolute error of the two is within 3dB. In summary, the PBNR curve obtained by the numerical simulation has a high consistency with the test curve, which verifies the accuracy of the vehicle SEA model.

5. TPNR analysis and acoustic package optimization

5.1. TPNR analysis

In order to measure the noise reduction effect of the vehicle acoustic package on tire noise excitation, the average TPNR (Tire Patch Noise Reduction) is used for evaluation [10], the calculation formula proposed in this paper is as follows:

\[
TPNR = \text{soud pressure level (internal)} - \text{soud pressure level (outside)}
\]  

Due to reciprocity, the sound source excitation in the testing and SEA numerical simulation work in this paper is all placed in the car, and the excitation collection is arranged outside the car. In formula (1), the external sound pressure level (dB) is obtained by averaging the sound pressure levels of all measuring points outside the car, and the internal sound pressure level (dB) is averaged by the sound pressure levels of all measuring points inside the car. get. Figure 4 below shows the TPNR result of the numerical simulation.
It can be seen from the above figure that the noise reduction effect of the car interior noise based on tire noise excitation increases with increasing frequency. Controlling the noise inside the car is to control the noise energy outside the car, the amount of transmission transmitted to the car, and the amount of sound absorption in the car [11]. For tire noise excitation, the noise outside the car has a great relationship with road conditions, tires, speed, etc., and it is not easy to control [12], so the external noise is used as the boundary condition to improve the sound absorption and sound insulation capacity of the car interior acoustic package. To reduce the noise in the car under the excitation of tire noise.

5.2. acoustic package optimization

Some studies [1] pointed out that the luggage compartment floor, front and rear floors, and front and rear wheel covers have a greater contribution to the in-vehicle noise excited by tire noise; This article mainly studies the above points and proposes the following optimization schemes:

1. Carpet optimization plan: increase the dual impedance coverage to more than 95%, while the dual impedance thickness of 25mm or more accounted for more than 70%, and 20mm accounted for 30%;
2. Luggage carpet optimization solution: double impedance + sound-absorbing cotton The plan, the sound-absorbing cotton is attached to the sheet metal side, the overall coverage is more than 95%, and the double impedance thickness is more than 20mm accounting for 70%, 15mm accounting for 20%, and 10mm accounting for 10%;
3. Optimization of rear wheel cover sound insulation pad: Using the dual-impedance + sound-absorbing cotton solution, the sound-absorbing cotton is attached to the sheet metal side, and the overall coverage rate is more than 95%. At the same time, the double impedance thickness is more than 20mm accounting for 70%, 15mm accounting for 20%, and 10mm accounting for 10%.

Aiming at the above three optimization schemes, they were verified in the SEA model of the vehicle, and the TPNR was calculated based on formula (2).

The figure above shows the improvement effect of TPNR after applying optimization schemes for three different positions. As can be seen from the above figure, the rear wheel cover optimization scheme and the luggage compartment carpet scheme are not ideal for TPNR improvement, and the carpet scheme has a better effect on TPNR optimization. The optimization effect is better. It shows that optimizing the acoustic material at the carpet can effectively inhibit the transmission of tire noise, especially in the high frequency range, with a maximum increase of about 5dB; and the optimization plan optimizes the rear wheel cover sound insulation pad and luggage, Did not achieve the ideal optimization effect. It may be that the basic scheme at the rear wheel cover and the trunk has reached the saturation effect on tire noise reduction, or it may be that the contribution of the transmission path is small, and the next step can be studied.
6. Conclusion

Through SEA simulation and analysis of the sound insulation performance of the acoustic package, it can provide guidance for the optimization of the acoustic package in the early design stage, shorten the development cycle of the car, and reduce the development cost.

Based on the SEA theory, this paper establishes the SEA model of a vehicle model, and compares the PBNR simulation analysis data with the test data. The absolute error is within 3dB, which verifies the accuracy of the SEA model.

In order to measure the noise reduction effect of the vehicle acoustic package on tire noise excitation, a TPNR calculation method is proposed, and the TPNR result of the basic model is calculated. Apply optimization schemes to the SEA model of the whole vehicle for the carpet, trunk, The rear wheel cover optimization scheme and the luggage compartment carpet scheme are not ideal for TPNR improvement, and the carpet scheme has a better effect on TPNR optimization. The optimization effect is better. It shows that optimizing the acoustic material at the carpet can effectively inhibit the transmission of tire noise, especially in the high frequency range, with a maximum increase of about 5dB; and the optimization plan optimizes the rear wheel cover sound insulation pad and luggage, Did not achieve the ideal optimization effect. It may be that the basic scheme at the rear wheel cover and the trunk has reached the saturation effect on tire noise reduction, or it may be that the contribution of the transmission path is small, and the next step can be studied. It can be seen that optimizing the front and rear floor acoustic packages can effectively improve the noise reduction performance of tire noise excitation.

Acknowledgement
This research was financially supported by two projects that the key technology of acoustic package development (011512.07) and the research on key technologies of road noise development for passenger cars (011907.03).

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