Sound Quality Prediction of Vehicle Door Closing Based on Experiment and Boundary Element Method

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Abstract. The sound quality of the vehicle door can only be improved after the testing vehicle has been manufactured. In this paper, a simulation model of the door system closing collision is established, and the vehicle test and the bench test are designed. In the vehicle test, according to the design characteristics of the door structure and the situation that the operating load cannot be obtained directly. The impact load on the door are simplified as the concentrated loads when the door is closed. The reference points are arranged near the location of the concentrated loads, and the number is twice of the concentrated loads. The acceleration response at the reference points are measured. In the bench test, the frequency response functions (FRFs) from the concentrated load points to the reference points are measured. Using the inverse matrix method, the value of the concentrated loads are obtained. A boundary element model is established and the concentrated load are applied to the model to collect sound pressure signals at the field point. The results show that the sound pressure values obtained by experiment and simulation are highly consistent. It shows that this method is feasible in predicting the sound quality.

1. Introduction
With the continuous escalation of consumption in the automotive industry, consumers are increasingly paying attention to the Noise, Vibration, Harshness (NVH) of the passenger cars. The first thing consumers encounter when buying a car is the door NVH, which has become a problem faced by Original Equipment Manufacturer (OEM). The subjective and objective evaluation of the sound quality of door closing is only after the prototype is produced, and the engineer is not fundamentally instructed to predict the sound quality. Therefore, it is necessary to predict the sound quality of the door in advance to fundamentally improve the sound quality.

David Hamilton [1] analyzed the main factors affecting the sound quality of door-closing collision, including: duration, amplitude, frequency distribution, etc. Based on the analysis of these influencing factors, the main influencing factors of door sound quality are analyzed using 3D drawing technology, and the subjective evaluation performance value of door sound quality is proposed, which provides a theoretical basis for door sound quality improvement. Ford Motor Technology Research Office [2] proposed that loudness and sharpness have a greater impact on the door impact sound quality, and proposed a design scheme for the door system sheet metal, door lock system and sealing system. Zhidong Zhang [3] established the finite element model and boundary element model of the door. First, the finite element model was used to perform the door closing collision analysis to extract the response speed of the set measurement points. The measured results were used as the boundary condition of the boundary element model. The analysis and calculation of the sound pressure signal at the set point of
the door panel system. Yang Chuan [4] established an optimization model with the goal of reducing the collision energy of door closing, and compared and analyzed the sound pressure level of sound radiation from door closing before and after optimization. The effectiveness of the optimization model for reducing noise sound pressure level is verified. Ouyang Lian-ge [5] used the cab finite element model to perform a free modal calculation and compared the results with the experimental modal. Confirm the accuracy of modeling, use LMS Virtual.Lab software to perform modal superposition, and then get the frequency response of the cab. Fang Yuan [6] estimated the electromagnetic vibration and noise characteristics of the electric vehicle powertrain during the design phase. According to the structural characteristics of centralized drive electric vehicle power assembly, a joint simulation method of electric vehicle power assembly noise analysis under multi-source dynamic excitation was established. Chen Jia-n [7] took an excavator cab as an example, and established a structural finite element and acoustic boundary element model. Based on the frequency domain inverse matrix method to solve the excitation load under working conditions. The modal-based forced response method is used to obtain the vibration speed response of the cab under this excitation. Luo Mingjun [8] established a finite element model of the automotive cabin cavity based on Hypermesh finite element software. Then it is imported into the SYSNOISE environment in NASTRAN format to build a single-region boundary element calculation model. Feng Lei [9] used a forklift cab as a research object, and applied the PML method and boundary element method to analyze and predict the external radiation sound field caused by the vibration of the cab structure. Deng Yongcheng [10] took the oil pan of a minicar engine as an object to study the control of the radiated noise of the oil pan. Zhao Yuwei [11] used the body-in-white model and the finite element model of the door to obtain structural modal information. The vibration velocity characteristics of the structure from 20 to 200 Hz were obtained and the boundary element model of the interior cavity was established. Zhao Jing [12] selected the engine mount position as the excitation force on the structural finite element model, and obtained the structural vibration response by modal superposition method. Using the vibration response as the boundary condition of the acoustic boundary element model, the acoustic sensitivity curve of a point in the vehicle is calculated.

In this paper, the sound pressure response of the target point and the acceleration response of the reference point are measured through the vehicle test, and the frequency response function from the excitation point to the reference point is measured through the bench test. Use the inverse matrix method to find the work force of the excitation point. According to the door structure of a new energy vehicle, its finite element model is established using finite element software. Boundary element model of the door was established using acoustic software. The obtained working force is taken as a boundary condition. Acoustic radiation analysis is performed on the established boundary element model to extract the sound pressure data of the field points. Comparative analysis shows that the measured values of the target point are in good agreement with the predicted values.

2. Load identification
When the system is subjected to an external excitation load \( f(t) \), the differential equation of the system is:

\[
M \ddot{x} + C \dot{x} + Kx = f(t)
\]

(1)

Where \( M \), \( C \), and \( K \) respectively represent the mass matrix, damping matrix, and stiffness matrix of the system.

Perform fast Fourier transform on equation (2) and convert the time domain to the frequency domain to obtain:

\[
H(\omega) = \frac{X(\omega)}{F(\omega)}
\]

(2)

Where \( H(\omega) \) is the frequency response function. It is an inherent property of the system.

The system is assumed to be linear and time invariant. When the system receives excitation loads \( F_1, F_2, ..., F_n \), the system has responses \( X_1, X_2, ..., X_m \), so the system response can be written as:
\[
\begin{bmatrix}
X_1 \\
X_2 \\
\vdots \\
X_m
\end{bmatrix} = \begin{bmatrix}
H_{11} & H_{12} & \cdots & H_{1n} \\
H_{21} & H_{22} & \cdots & H_{2n} \\
\vdots & \vdots & \ddots & \vdots \\
H_{m1} & H_{m2} & \cdots & H_{mn}
\end{bmatrix} \begin{bmatrix}
F_1 \\
F_2 \\
\vdots \\
F_n
\end{bmatrix}
\]

(3)

Where \(H_{mn}\) is the frequency response function from the excitation point load \(F_n\) to the reference point \(X_m\).

The excitation point load can be obtained by multiplying both sides of equation (3) by the inverse matrix of the frequency response function:

\[
\begin{bmatrix}
F_1 \\
F_2 \\
\vdots \\
F_n
\end{bmatrix} = \begin{bmatrix}
H_{11} & H_{12} & \cdots & H_{1n} \\
H_{21} & H_{22} & \cdots & H_{2n} \\
\vdots & \vdots & \ddots & \vdots \\
H_{m1} & H_{m2} & \cdots & H_{mn}
\end{bmatrix}^{-1} \begin{bmatrix}
X_1 \\
X_2 \\
\vdots \\
X_m
\end{bmatrix}
\]

(4)

3. Data collection

3.1 Vehicle test

The test object is the left front door of a new energy vehicle, and the test is carried out on an equipped vehicle. The test system mainly includes sensors, data acquisition and recording systems, and working condition control devices. The microphone is a built-in ICP omnidirectional microphone produced by B & K Company, and the acceleration sensor is a structural test ICP three-direction acceleration sensor manufactured by PCB Company. LMS SCADAS III SC316-UTP data acquisition system and LMS Test. Lab test data processing and analysis system are used. The door closing speed is controlled by a door closing speed meter and a rubber rope energy storage device.

![Figure 1. Microphone position](image1)

![Figure 2. Door closing speed meter and rubber rope energy storage device](image2)

In the vehicle test, the microphone was arranged at the user's right ear position at the door opening outside the vehicle to collect sound pressure signals. The position of the microphone is 1.0m outward from the left front door and 1.6m above the ground, pointing to the body side, as shown in Figure 1. Door closing speed meter and rubber rope energy storage device are used to control the door closing speed, as shown in Figure 2.

In this section, the working load when the door is closed is discretely concentrated into 11 degrees of freedom. The load on the seal is discretely concentrated into 8 degrees of freedom (S1~S8). The load on the lock is dispersed into a concentrated load (L1) with 3 degrees of freedom, and the direction is the X Y Z direction, as shown in Figure 3. When using the inverse matrix method to obtain the working point load, the degree of freedom of the reference point is required to be more than twice that of the working point, the degree of freedom of the reference point is 48 (X1 ~ X16), and the direction is X Y Z direction, as shown in Figure 4. Meet the calculation requirements of the inverse matrix.
method. Paste the three-direction acceleration sensor to the position of the working point and the reference point.

![Figure 3. The position of working points](image1)

![Figure 4. The position of reference points](image2)

### 3.2 Bench test

The bench test system is mainly composed of two parts: an excitation and measurement system, a data acquisition system. The excitation system is mainly a force hammer. Modally Tuned ICP impact hammer manufactured by PCB company is used as the exciter. The measurement system and data acquisition system are the same as the vehicle test.

![Figure 5. Bench test](image3)

In order to approximate the boundary conditions required by the actual structure of the door, the door fixture is designed, the door is fixed on the fixture, and its frequency response function is measured, as shown in Figure 5. The natural frequency of the tested fixture is much higher than that of the door, and the fixture meets the experimental requirements. The analysis frequency range of this paper is 0–200Hz. Hit the working point as shown in Figure 3 with a hammer, paste a three-direction acceleration sensor at the reference point as shown in Figure 5, and the frequency response function from each working point to the reference point can be measured, as shown in Figure 6. The working force of the working point can be obtained by formula 4, as shown in Figure 7.
4. Simulation analysis

This section briefly introduces the process of establishing the finite element model of the left front door. Sheet metal parts and glass use shell elements, sealing strips, structural glue and hinges use hexahedral elements. The number of finite element model elements is more than 130,000. The door structural materials are mainly stamped steel plates, and its main mechanical performance indicators are yield strength and tensile strength. The names, materials, and performance parameters of the main door structures are shown in Table 1.

| Component      | material | Yield Strength (MPa) | tensile strength (MPa) |
|----------------|----------|----------------------|------------------------|
| Outer panel    | HC180B   | 205                  | 330                    |
| Inner panel    | DC04     | 210                  | 270                    |
| Reinforcing plate | DC01    | 260                  | 270                    |
| Hinge          | Q345     | 345                  | 490                    |

Boundary element method is a calculation method for discrete problems proposed after finite element. The finite element method is a global discretization. The boundary element method only discretizes the boundary, which can more accurately simulate the original model than the finite element method. It retains the information of the original model more completely and reduces the dispersion error.

The door structure in contact with the air is discretized into a finite number of element, and the mesh size of the boundary element model is 5 mm. Y-direction excitation load is applied at the discrete points (S1~S8) of the sealing strip, and X, Y, Z-direction load excitation is applied at the lock (L1). The excitation load value is shown in Figure 7. The fluid medium is defined as air, the speed of sound is 340m/s, the density is 1.225kg/m², and the coordinates of the response point are X=2500mm, Y=-1000mm, Z=1600mm, as shown in Figure 8.
The modal information of the door is imported into the boundary element and calculated. Then calculate the sound pressure level at the field point according to the sound pressure level calculation formula.

$$P_{db} = 20\log_{10}(\frac{p}{p_0})$$

(5)

Where $P_0$ is the standard sound pressure, and the value is $2\times 10^{-5}$Pa.

The frequency curve of the sound pressure level of the microphone at the set field point is shown in Figure 9. It can be seen that the simulation curve agrees well with the experimental curve, and the effectiveness of the prediction of the door closing sound is valid.

5. Conclusion
This paper designs vehicle tests and bench tests. In the vehicle test, the sound pressure level curve at the target field point and the vibration acceleration response at the reference point are obtained when the door of a passenger car is closed. The frequency response function from the discrete excitation point to the reference point was obtained in the bench test. Using the inverse matrix method, the vibration acceleration response at the reference point, and the frequency response function from the discrete excitation point to the reference point, the working load at the discrete excitation point is obtained. This paper also establishes a finite element model of the vehicle door closing collision simulation analysis to obtain the modal information of the door, and imports the modal information into the boundary element model. The calculated working load at the discrete points is input to the boundary element model, and a field point is set at the target point to collect the sound pressure signal. Finally, the data obtained from the simulation are compared with the data measured by the test. The validity and feasibility of the method are verified.

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