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Improvement of interior sound quality for passenger car based on optimization of sound pressure distribution in low frequency

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ABSTRACT

The low-frequency acoustic response model of car is established with finite element method (FEM) and boundary element method (BEM), and the model is validated via road test. Utilizing the equal rectangle bandwidth critical band within 20–200 Hz, the 16 sound samples are designed by orthogonal experiment with the collected signal of driver at 50 km/h as example. The psychoacoustical indices of each sample are calculated through the program compilation, and the annoyance of each sample is obtained via subjective test. The prediction model for sound quality is completed under the comprehension of genetic algorithm (GA), particle swam optimization (PSO) and support vector machine (SVM). Taking the sound pressure level of each equal rectangle bandwidth band in low frequency as variables and taking the minimal subjective annoyance of samples as optimization objective, an optimization model for sound quality is established. Subsequently, the optimal sound quality is obtained. An extra subjective evaluation validates this proposed optimization method.

1. Introduction

With the improvement of requirements for noise, vibration, harshness (NVH) performance, interior sound quality (SQ) in passenger cars has been the focus of attention among car manufactures. Up to now, a lot of researches on the evaluation of sound quality related to finished structures or products of automotive, such as interior noise in cars [1,2], door closing sound [3–4], window motors [5], engine sound [6], etc. have been presented. And the evaluation approaches currently are mainly including objective evaluation and subjective evaluation as in the case of the evaluation of the soundscape quality [7]. In objective evaluation, objective parameters like loudness, sharpness, fluctuation, roughness, etc. are selected to describe the sound quality of samples. And the efforts are focused on finding some better objective parameters to predict the sound quality. Y.S. Wang estimated sound quality for interior and exterior vehicle noises with discrete wavelet transform [8]. Yang Chuan proposed a sound metric based on pseudo Wigner-Ville distribution for door closing sound [9]. Hai B evaluated sound quality of vehicle suspension shock absorber rattling noise based on the Wigner-Ville distribution [10]. The subjective evaluation which is the reflection of auditors includes semantic differential, anchored semantic differential and pair-comparison method. Combination of the two evaluations, that explores the crucial objective metrics and the prediction model with mathematic tools like regression, genetic algorithm method (GA) [11,12] and support vector machine (SVM) [13,14] is widely adopted for sound quality evaluation and prediction.

Many industries are taking advantage of the guiding effect based on analysis of sound quality by computer aided engineering (CAE) technique, such as Herman Van established a virtual audio environment of automotive and evaluated the sound quality of synthesis sample which guides to improve the interior acoustic design for CAE model and shorten the development period [15]. Rene Visser improved the sound quality of commercial vehicle in low frequency domain with combination of transfer path analysis (TPA), virtual prototype and finite element method (FEM) [16]. Avnish Gosain and Mugundaram Ravindran amended powertrain mount bracket with the target of sound quality of interior acoustic [17]. Therefore, if we take sound quality of product as a target during early design process and explore a better acoustic feature in frequency domain, the cost of time and money will be reduced significantly.

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However, there is a lack of the method to realize the acoustic prediction in full frequency domain which is the precondition for evaluating sound quality. Widely used FEM and BEM cause interpolation error and contaminated error because of element discretized and shape function, so they have a high calculation cost in high frequency. Hence, utilization of methods based on elements are common in solving problems of sound and vibration at low frequency. Statistical energy analysis (SEA) and mixed FEM-SEA cannot get definitive response since both methods are statistically averaging in time and space [18,19]. Hence, since energy of interior noise is mainly conserved in low frequency, the thought of this study is presented just through mainly talking about the interior noises in low frequency which have great influence on occupant comfort. Based on this point, simulating the interior acoustic response utilizing mature commercial analysis tool in low frequency and analyzing the distribution of sound pressure in frequency domain to improve sound quality shows great engineering value for providing a reference for design and improvement of products. Furthermore, the sound quality of developed products would be improved via optimizing the primary structures that have the major contribution effects on corresponding frequency.

From the above discussion, a passenger car is taken as an example to validate our ideas. Its acoustic response model established with FEM-BEM is validated through a real test. Different sound samples are designed based on original sample divided by ERB critical band in 20–200 Hz. Accordingly, calculation of objective parameters and subjective evaluation test of each sample are completed. SVM model to predict sound quality is built with GA and PSO. On the basis of the prediction model, establishment of optimization model for sound quality is finished with taking sound pressure level (SPL) of each ERB band as variables. Optimization for sound quality of all the samples are realized and verified.

2. Establishment and verification of FEM-BEM model

2.1. Establishment of model with FEM-BEM

An accurate numerical prediction model is the foundation of analysis and subsequent optimization for sound quality. Geometric model of a real car is meshed, in which thin-walled plates are discrete using shell elements and other parts are simulated with body element. Some complicated structures which are not parts of body of vehicles like power assembly are modeled with rigid elements [20,21]. Parameters of element quality index are listed in Table 1. The completed finite elements model is shown in Fig. 1(a). Interior acoustic cavity is calculated with BEM for higher computational efficiency. Based on the finite element model, an acoustic model is built in Hypermesh Acoustic Cavity Mesh. Elements on the surface of the model are extracted to establish initial boundary elements. Parts of body panel which have a contact with air are formed after repairing and adjusting local details. Size of boundary elements model is 40 mm. Considering that shapes and structures of seats and passengers have effects on characters of interior sound field, and acoustic impedance of the surface affects distribution of sound field, the surfaces of seats and passengers are modeled with boundary element method. The boundary element model is shown in Fig. 1(b). Acoustic impedances of these parts are shown in Table 2.

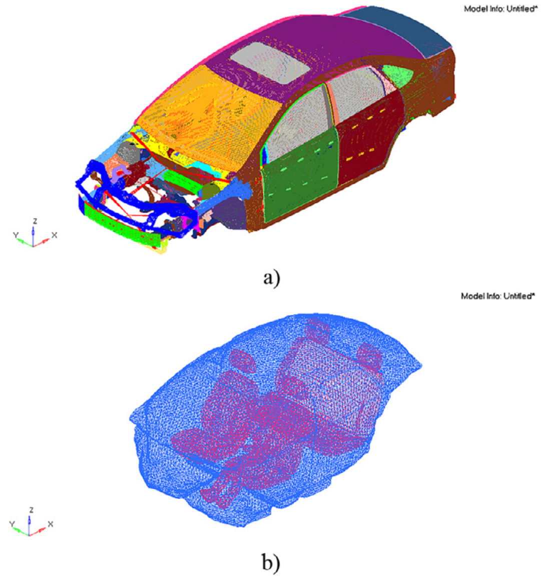

Fig. 1. Element based model: (a) Finite element model of car body; (b) Boundary element model.

2.2. Acoustic acquisition and model validation

The test system for sound and vibration produced by Brüel & Kjær is adopted. Seven accelerometers are arranged at three mounting positions of engine and four upper supporting points of suspensions. Microphone B&K4189 is placed at the driver's right ear according to GB/T 18697.The arrangement of sensors is shown in Fig. 2.

To validate the model adequately, tests under four working conditions are conducted with real car on city road: idling, 30 km/h, 40 km/h, 50 km/h. Vibration responses of acceleration sensors and acoustic responses of microphones at driver's right ear are acquired in test. Then vibration responses are loaded on the FEM-BEM model. Acoustic responses at driver's right ear in prediction model are calculated. In Fig. 3, acoustic responses obtained in test and prediction model at 30 km/h from 20 to 200 Hz are compared. It shows that analytical precision of prediction model below 200 Hz is reliable. Fig. 4 shows comparison at 50 km/h. Root-mean-square error (RMSE) and error rate of peak value are shown in Table 3, which illustrates the validity and usability of the model. The procedure for calculating the error rate is following:

$$RMSE = \frac{SPL_{pre} - SPL_{mea}}{SPL_{mea}} \times 100\% \qquad (1)$$

Table 1
Parameters of element quality index.

Parameters of element quality index	Standard value
Target element size	8 mm
Min Size	4 mm
Max Size	13 mm
Aspect Ratio	5
Warpage	15
Skew	40
Jacobian	0.7

Table 2
Acoustic impedance parameters in each area.

Part	Acoustic impedance/kg_m2_s
Seat	975 + 8798 j
Passenger	970 + 8800 j
Roof	830 + 3030 j
Floor	751 – 6640 j
Side panels	830 + 3030 j
Front wall	900 + 5700 j