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Simulation on a Car Interior Aerodynamic Noise Control Based on Statistical Energy Analysis

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Abstract: How to simulate interior aerodynamic noise accurately is an important question of a car interior noise reduction. The unsteady aerodynamic pressure on body surfaces is proved to be the key effect factor of car interior aerodynamic noise control in high frequency on high speed. In this paper, a detail statistical energy analysis (SEA) model is built. And the vibra-acoustic power inputs are loaded on the model for the valid result of car interior noise analysis. The model is the solid foundation for further optimization on car interior noise control. After the most sensitive subsystems for the power contribution to car interior noise are pointed by SEA comprehensive analysis, the sound pressure level of car interior aerodynamic noise can be reduced by improving their sound and damping characteristics. The further vehicle testing results show that it is available to improve the interior acoustic performance by using detailed SEA model, which comprised by more than 80 subsystems, with the unsteady aerodynamic pressure calculation on body surfaces and the materials improvement of sound/damping properties. It is able to acquire more than 2 dB reduction on the central frequency in the spectrum over 800 Hz. The proposed optimization method can be looked as a reference of car interior aerodynamic noise control by the detail SEA model integrated unsteady computational fluid dynamics (CFD) and sensitivity analysis of acoustic contribution.

Key words: car, interior aerodynamic noise, control, computational fluid dynamics, statistical energy analysis

1 Introduction

The aerodynamic pressure on the car surfaces is one of the important power inputs of car interior noise in high frequency at high speed[1–2]. The aerodynamic power inputs on autobody surfaces are transferred by the structures[3–5]. Bremner's and CordioliI's researches show that the process is that when the aerodynamic pressure on car surfaces transfers the energy through the body structures, besides the power loss[6–7], some energy is preserved in the structures subsystem as vibration and some is transferred from structure subsystem to cavity subsystem by the coupling connection. The energy transfer of aerodynamics happens among the exterior flow, the structures and the interior acoustic space in the aero-vibro-acoustics model.

The aerodynamics is the important effect factor of car interior noise analysis in high frequency. From the existing literatures, the domestic research of car noise reduction in high frequency mostly focuses on exterior noise, or uses relative simpler SEA models[8–10], for example Jin's, Gong's and Yang's work. Thus, using a complicated detailed SEA model to analyze and reduce the interior noise in high frequency is quite challenging.

A new simulation way is introduced in this paper to get the aerodynamics pressure for the analysis model of car interior noise. It is a good way to cut down the development time and cost, and further improve the availability and efficiency in car interior noise analysis and control. After the introduction to simulation model and its building procedures, this paper further employs the sensitive analysis of the power input to the interior noise to establish the most sensitive subsystems. Then, the conclusion is reached that, after the further vehicle testing verification, the materials optimization-improving sound and damping properties of those subsystems can reduce the sound pressure level of car interior aerodynamics noise.

2 Simulation Model

The model subsystems should be reasonable, the materials properties should be accurate, and the power inputs from exterior aerodynamic and the powertrain should be loaded exactly, so that the model can be used to analyze and control the interior aerodynamics noise.

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2.1 Model building

Firstly, based on a 3D digital model of the vehicle body and the principles of modal similarity, structural subsystems are divided to build the SEA model. The auto body steel panels, windshield and other windows glass are built as SEA plates and curved shells subsystems. Some beam structures are built as SEA beams subsystems. The entire structure of the car body is divided into 64 plates or curved shells subsystems and 17 beams subsystems.

Secondly, the occupant cavity is divided into five detailed SEA cavity subsystems for accurate responses at different locations, since the gross acoustic responses can be only obtained by using the SEA method. Therefore, there are all together six cavity subsystems including trunk cavity. The SEA model of autobody structure and cavities are shown in Fig. 1.

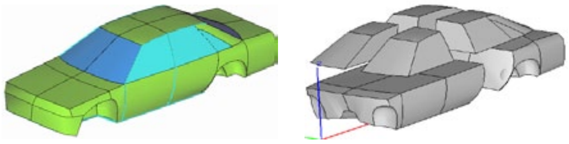

Fig. 1. SEA model of autobody structure and cavities

For the energy can be transferred among particular subsystems, the structural and acoustic cavity subsystems, they share common nodes or faces through points, lines or areas junctions. The subsystems are defined in terms of their physical properties. The material properties used in this research are steel (body panels and beams), laminated glass (windshield), tempered glass (rear, side and quarter windows) and air (interior cavities). The structural parameters must be provided according to the car structures, such as the thicknesses of the panels and the glass, the beams' sections areas and principal moments of inertia, and so on.

2.2 Model inputs

2.2.1 *Powertrain inputs*

The powertrain inputs obtained from experiments under the general running conditions are the accelerations on the engine mounts, and the sound pressure of the engine bay. The equipment used were acceleration sensors, charge amplifiers, microphones, sound level meters, data acquisition systems, computers, and so on. The flow chart is shown in Fig. 2.

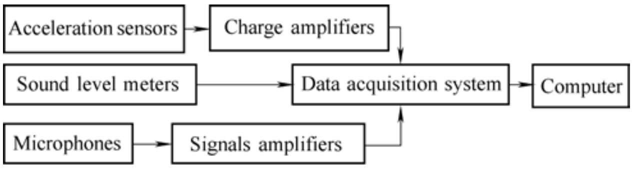

Fig. 2. Flow chart of experiments

Some photos of the car, the test instrumentations are shown in Fig. 3. The location of the accelerometer on right rear engine mount, and the location of one microphone in the engine compartment are shown in Fig. 4.

Fig. 3. Testing vehicle and instrumentations

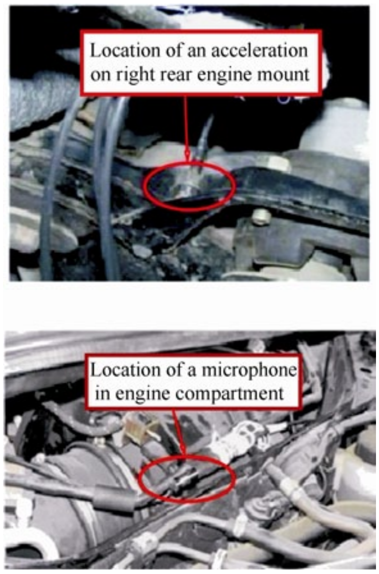

Fig. 4. Locations of the accelerometer on right rear engine mount and one microphone in the engine compartment

The accelerations on the engine mounts can be measured in the experiment order, which are the power inputs from powertrain to the car body at 100 km/h. Fig. 5 shows the spectra of acceleration on powertrain mounts at 100 km/h.

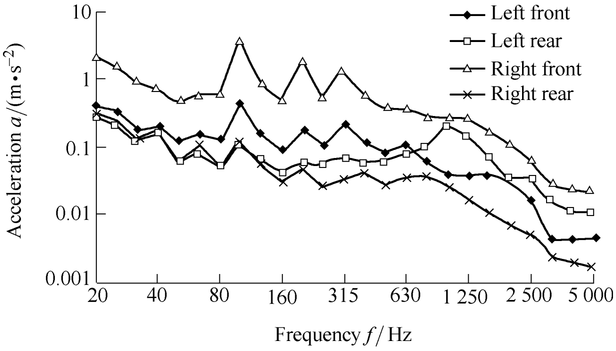

Fig. 5. Spectra of accelerations on the different powertrain mounts at 100 km/h

The sound pressure in the engine compartment can be processed into the spectrum of sound pressure level. Fig. 6 shows the 1/3 octave band spectrum of sound pressure in the engine compartment at 100 km/h.

2.2.2 *Aerodynamics inputs*

Fig. 7 shows the sketch map of computational domain (half car) of CFD wind tunnel simulation testing. L is the length of the car; H is the height of the car; and W is the width of the half car. Therefore, the size of the computational domain for the simulation in wind tunnel is: Height is $5H$; Width is $5W$; Length is $9L$; The distance from tunnel inlet to car is $2L$; The distance from tunnel outlet to car is $6L$[10–12]. Mesh should be generated after the determining of computational domain. The way of mesh generation of computational domain (especially exterior flow field of complex car shape) is an important matter of CFD and its application research. It does not only influence the domain discretization itself, the final form of differential coefficient equations, but also the whole process of fluid numerical calculation.

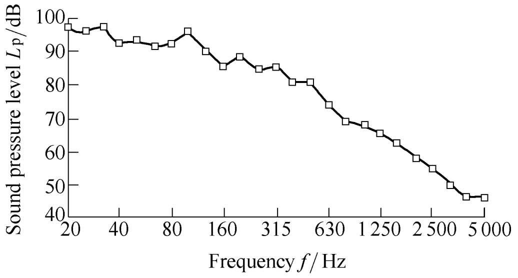

Fig. 6. 1/3 octave band spectrum of sound pressure in the engine compartment at 100 km/h

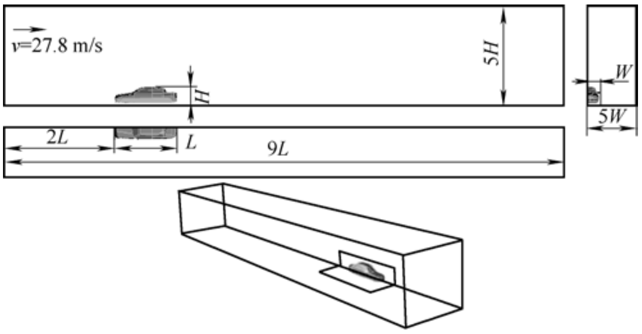

Fig. 7. Sketch map of computational domain (half car) of CFD wind tunnel simulation testing

The grid types of flow analysis are unstructured grid and structured grid. The mesh scheme of this paper is the mixed mesh based the characteristics of the research objects and the research experiences, which is triangular prism mesh+tetrahedral mesh+hexahedral mesh+polyhedral mesh[13–15]. Car CFD simulation mesh of symmetry plane of wind tunnel (y=0, partial) and the autobody surfaces mesh are shown in Fig. 8.

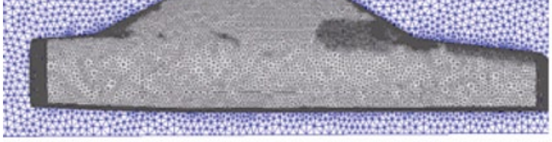

Fig. 8. Car CFD simulation mesh of symmetry plane of wind tunnel (y=0, partial) and the autobody surfaces mesh

The locations of A-pillar, front side mirror, windshield wiper, antenna and sealing stripe, etc, are the most violent changes of aerodynamic pressure on car surfaces in the exterior flow[16–18]. Fig. 9 shows the three-dimensionally separated flows from A-pillar and front side mirror[19].

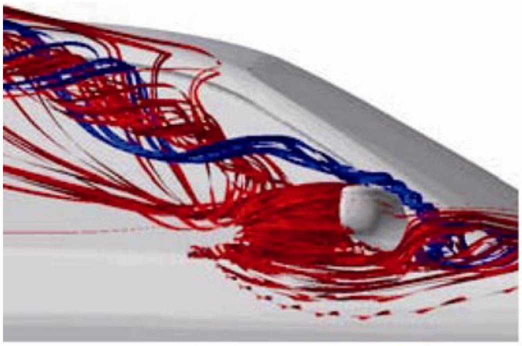

Fig. 9. Three-dimensional separated flows from A-pillar and front side mirror

Fig. 10 shows the front door window measurement locations. The 6 monitoring points of aerodynamics pressure on front door window surface were located in this research[20–22]. The time step was 0.1 ms, the steps was 500, so the sampling time was 0.05 s. After the unsteady iterative calculation, the aerodynamics pressure of every monitoring point was obtained. Then, the 1/3 octave band spectrum of average aerodynamics pressure was achieved.

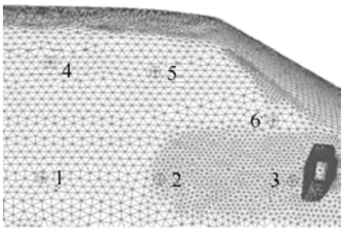

Fig. 10. Locations of 6 monitoring points of aerodynamics pressure on car body surfaces

The 1/3 octave band spectra of aerodynamics pressures on monitoring points and the average pressure spectrum are shown in Fig. 11.

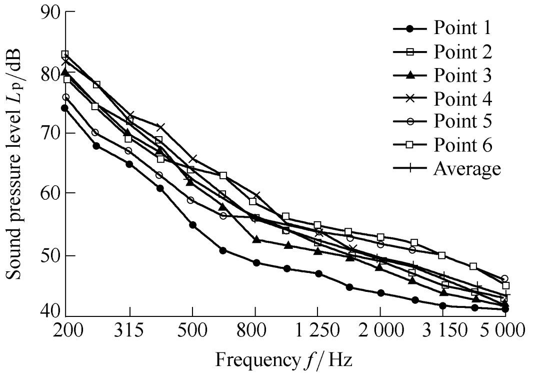

Fig. 11. 1/3 octave band spectra of aerodynamics pressures on monitoring points and the average pressure spectrum

From Fig. 11, it shows that the pressure on monitoring point 6 is higher than the other points on most octave band central frequency, especially, the frequency from 630 Hz to 5 000 Hz. This is that point 6 locates between the A-pillar and the front side mirror, where is the most violent in the complex turbulent region of airflow. The pressure of monitoring point 5 is also high in the frequent region from 1 000 Hz to 5 000 Hz. But the pressure of point 1 is always lower than the others', for that the location of point 1 is far away from the complex turbulent region. They all accord with the distribution law of general aerodynamics characteristics on autobody surfaces[23–25].

3 Simulation Analysis

The aerodynamics pressure spectrum was input to the simulation model together with other power inputs from powertrain, vibration and acoustic radiation. After the inputs were loaded, the response analysis of car interior noise can be calculated using the detailed vibro-acoustic model. As is shown in Fig. 12, the measurement and simulation spectra of sound pressure level in the driver's head cavity at 100 km/h (27.8 m/s). It can be seen that a little deviation between predicted and measured curve in lower frequency band is below 630 Hz. This is related to the application characteristics of SEA theory. One reason for this deviation is that the modal density is low in this frequency range. The other reasons are the effects of structures, leaks, holes and the errors in measured damping loss factor (DLF), and so on, are not considered. But in higher frequency range (over 800 Hz), the testing data matches the calculated data very well. The range of deviation is less than 3 dB at every frequency point over 800 Hz. This shows that the SEA model is effective for analysis and noise control in high frequency.

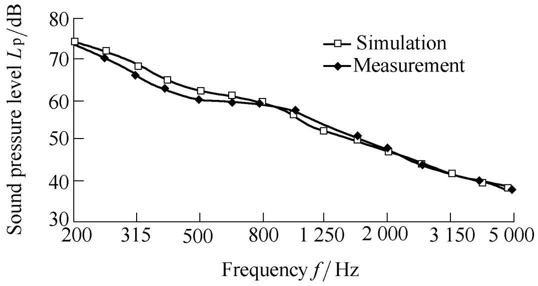

Fig. 12. Measurement and simulation spectra of sound pressure level in the driver's head cavity at 100 km/h

By the simulation analysis of all the power inputs, the different subsystems' power inputs to the interior sound cavity are different. Fig. 13 shows the power contribution of some subsystems, such as fenders, dash, windshield, rear window, doors and roof to the interior sound cavity. It shows that the power contribution of dash, front doors and fenders are larger than other panels in high frequency range. Otherwise, unity power inputs of dash fenders and the front doors are larger than the others. So the dash, front doors and fenders are the focus control panels of power inputs to the interior sound cavity.

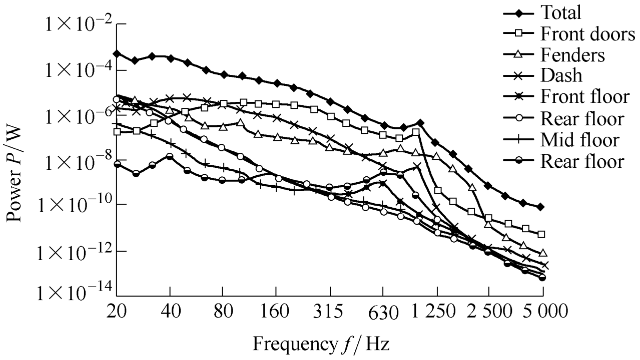

Fig. 13. Power inputs of some subsystems to the interior sound

4 Optimization Processing

As is shown by the measurement data curve in Fig. 12, the sound pressure level of driver's head cavity at every frequency band is high from 200 Hz to 5 000 Hz. Therefore, the application of absorption material and the damping material can get good noise reduction effect in the mid and high frequency.

Acoustic materials database for vehicle (AMDV) is a good database system built by Jilin University NVH group. By the AMDV, a kind of resin fiber (3 mm thickness and 144 kg/m^3) can be found and it can be used to reduce the sound pressure level, especially in mid and high frequency. The sound absorption characteristic of this kind resin fiber is shown in Fig. 14.

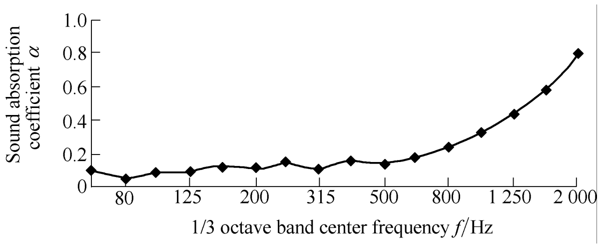

Fig. 14. Sound absorption characteristic of resin fiber

Fig. 15 shows the sound pressure levels of driver's head cavity before and after improving the sound absorption characteristics of fenders, dash (both sides), front door, ceiling and coat rack, and thickening the damping materials of fenders and dash.

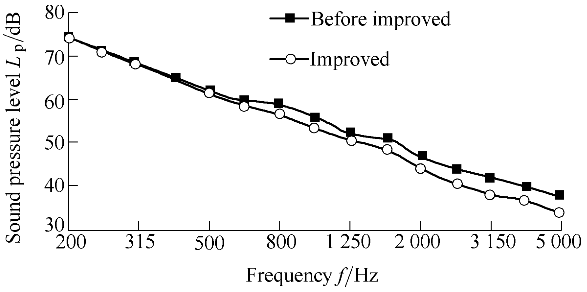

Fig. 15. Sound pressure levels of driver's head cavity before and after improving the absorption materials and thickening the damping layer

5 Testing Verification

Fig. 16 shows the testing of absorption material (3 mm) and damping material (2 mm) on dash and fender panels of both sides.

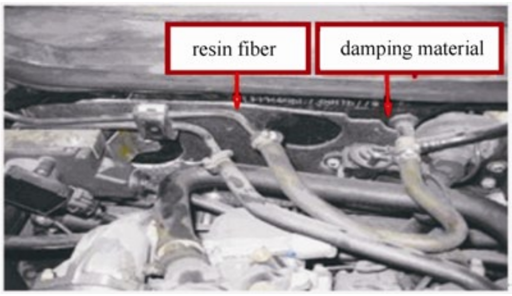

Fig. 16. Testing of absorption and damping materials

Table 1 shows the sound pressure level data of driver's head cavity before and after the improvement at different velocities.

Table 1. Sound pressure level data of driver's head cavity before and after improvement dB(L)

No.	Condition	Before improved	Improved
1	Background	58	63
2	Idling	78	80.5
3	Fourth gear 50 km/h	101	98.5
4	Fifth gear 60 km/h	102	101
5	Fifth gear 70 km/h	104	102.5
6	Fifth gear 80 km/h	105	102
7	Fifth gear 90 km/h	107	103
8	Fifth gear 100 km/h	108	105.5
9	Fifth gear 110 km/h	110	106

As is shown in Fig. 17, after improving the sound absorption characteristics and thickening the damping layer of fenders and dash, the sound pressure level of driver's head cavity reduces a little bit at every constant running condition except at idling condition (the background effect) where the sound pressure level increases by 2.2 dB. The average reduction of sound pressure level of driver's head cavity is 2.64 dB. And, the reduction at 80–110 km/h is 2.5–4 dB, which is almost consistent with the simulation result data. Therefore, the noise control way and the simulation result in the paper are effective.

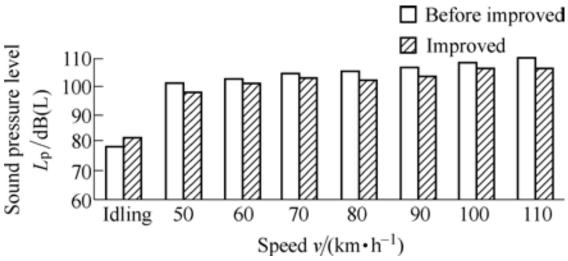

Fig. 17. Sound pressure levels of driver's head cavity before and after improvement

6 Conclusions

(1) Putting forward a new method of calculating the power inputs on body surface by using CFD simulation wind tunnel experiment, thus offering a complement to the old and difficult SEA method used during the early period of the car development to acquire the aerodynamic power input on surface, which is the base of improving the accuracy of building the SEA model and predicting the interior noise.

(2) Identifying the dash panel, front fenders and the front doors as the sensitive panels of power inputs to driver's head sound cavity through the analysis of unity and actual power inputs on every subsystems of SEA model, which applies the analysis base of car interior noise control.

(3) Deducting from the results of the simulation verification experiments that the control programs in this paper can achieve a good noise reduction result and can be as a significant guide for the concept design in the new car development.

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