ANALYSIS OF INTERIOR NOISE OF AN ELECTRIC VEHICLE AT HIGH SPEED

Wu Xian, Liu Jitian, Shao Jianwang*, Deng Guoming

Tongji University, No.4800, RD Caoan, District Jiading, Shanghai, China

* Corresponding author, email: shaojianwang@tongji.edu.cn

Interior noise of a battery electric vehicle in high speed is studied in this paper. From the perspective of practical engineering application, the interior sound pressure level (SPL) of the electric vehicle under the working condition of 30m/s is analyzed based on the Corcos model, the Diffuse Acoustic Field (DAF) model, the boundary element method (BEM) and the statistical energy analysis (SEA) method. The accuracy of the methods was verified by comparison with the experiment. The influence of different thickness of side window glass on the SPL of the driver's head cavity is analyzed, which can guide the design of body material parameters and sound package.

Keywords: interior noise, electric vehicle, corcos model, diffuse acoustic field

1. Introduction

For the Electric Vehicle (EV), as the speed of the car increases, high-speed wind noise becomes the main source of noise. The high-speed car interacts with the airflow to form a boundary layer on the surface of the vehicle body. The presence of the exterior attachments and the slits creates a strong separation flow and reattachment flow in the boundary layer. The turbulent vortex shedding and crushing cause strong Fluctuation Surface Pressure (FSP) on the body surface, which is the source of aerodynamic noise outside the vehicle. P. Shorter [1] established an example to prove that Diffuse Acoustic Field (DAF) has greater penetration into glass under the same size of Turbulent Boundary Layer (TBL) and DAF. Paul G. Bremner [2] found that there are not only DAF but also propagating sound field and free space excitation in turbulent fluctuation pressure. In order to establish a mathematical model of two main excitations of TBL and sound field components, a large number of experimental studies have been carried out. Among them, TBL occupies most of the pulsating pressure, it is the main source of 400-2000Hz noise inside the vehicle [3]. The single point surface pressure model proposed by Smol' yakov [4] and Goody [5] is the most accurate, and the normalized wave number-frequency spectrum model proposed by Corcos [6] is predicted to be large in some cases. P. Bremner [7] successfully extracted the sound field components of the vehicle body surface using a high-resolution microphone.

In this paper, the external flow field of the whole vehicle is firstly analyzed. Then, the convective component and sound field component are extracted based on Corcos model and the boundary element method (BEM). Based on a validated full SEA vehicle model, the interior sound pressure level (SPL) of the electric vehicle is studied and the simulated results are validated by the test data. The front side window glass is finally optimised to reduce the SPL of the driver's head cavity.
2. Setting and solving of the external flow field of the whole vehicle

2.1 Establishment of geometric model and calculation domain

Based on the CATIA model of a EV, the gap between the various parts of the body is filled, such as the gap between the door and the door frame, the engine compartment cover and the engine room, and the holes are re-established. The surface ensures that the entire body is a closed surface, and ignores the details of the department's body, such as door handles, wipers, chamfers, etc., The rear view mirrors, tires and other components that have a great impact on the flow field outside the body are retained. Appropriate simplified model can not only improve the quality of the grid, improve the accuracy of the calculation results, but also shorten the calculation time. Finally, the three-dimensional model of the electric vehicle is shown in Figure 1. The overall vehicle size is 4018 mm in length(L), 1860 mm in height(H), and 1600 mm in width(W). Since the vehicle body exhibits a symmetrical structure, half of the body can be selected for CFD numerical calculation to reduce the calculation amount without affecting the accuracy of the solution result.

Figure 1: Processed vehicle geometry model

In order to realistically simulate the external flow field of a car, the calculation domain of the flow field must be established around the semi-body to simulate the effect of the car in the wind tunnel, so the calculation domain should be designed to be large enough to ensure a uniform flow of air through the surface of the car. The length of the calculation domain should be 6 times the full length of the outer contour of the model, and the width should be greater than twice the width of the outer contour of the calculation model. In this simulation, the length is 11 times, the width is 7 times, and the height is 5 times that of the model studied. Therefore, the size of the calculation domain is 11L×7W×5H.

2.2 Computational mesh

Hypermesh is used to divide the grid of the computational domain and the body surface. Triangular units are used to mesh the vehicle surface while hexahedral units are for the far field, and the boundary layer mesh uses prismatic units. Finer mesh is used near the rear view mirror and the A-pillar. The mesh size is 2mm, and then gradually transitions to the body's mesh size of 15mm. The final mesh number is about 12 million. The grid of the area near the body is shown in Figure 2. The grid quality of the entire computational domain is high, which can improve the convergence speed and the accuracy of the calculation results.

2.3 Boundary conditions and solver settings

The inlet condition is velocity-inlet and the flow rate is 30 m/s. In order to avoid the non-physical solution of the inlet stagnation point parameter, the simulated flow field is set to composed of incompressible fluid. The outlet condition is set to a pressure-outlet of 0 Pa. The Reazible k-epsilon turbulence model is used to solve the problem. The time step size is set to 5e-5s, and the number of time step is set to 5000. Thus, the number of iterations in a single step is 25.
2.4 Analysis of numerical simulation results of external flow field

Numerous studies have shown that the Fluctuation Surface Pressure on the surface of the car body is the main source of noise, whether it is aerodynamic noise inside the car or outside the car. These fluctuation pressures are mainly due to the eddy caused by the A-pillar and the rear view mirror. Figure 3 shows the vehicle pressure distribution cloud map. As can be seen, a positive pressure is generated at the forefront of the vehicle body, in front of the rear view mirror, and at the wiper position. A negative pressure is generated at the place where the airflow is separated. Positive pressure is also generated in front of the tire, and the pressure distribution on the side of the side body is uneven.

Since there is eddy at the position of the protrusions such as the A-pillar and the rear view mirror, the pressure distribution on the side window is large, and the front side window is close to the driver's head, which causes the flute pressure of the front side window to become the main noise beside the driver's ear. As can be seen from Figure 3, there are three regions on the side window, which are the separation region caused by the A-pillar, the separation region caused by the mirror, and the reattachment region at the rear of the side window. In the pressure profile on the surface of the mirror, the positive pressure in the flow direction is maximum, and then a pressure gradient is generated on the surface of the mirror, and the pressure is gradually reduced until the negative pressure on the back side of the mirror.

3. Extraction of convective component and sound field component

3.1 Convective components extraction through Corcos model

In this paper, it is assumed that the entire side window fluid surface pressure distribution is uniform, and the side window is considered as an integral area. A model for extracting convective components is established in VA One, wherein the fluid surface pressure of the vehicle body surface is shown in Figure 4. As can be seen, as the frequency increases, the amplitude of the pressure on the surface of the vehicle body gradually decreases, and the fluid surface pressure of the A-pillar and the mirror region is the largest.

The four parameters of the Corcos model in each region of the vehicle body are calculated separately. The spatial average pressure $\Phi(\omega)$ and the convection wave number $K_c$ of the Corcos model in the front side window region are shown in Figure 5. The spatial average pressure $\Phi(\omega)$ produces a peak at 720Hz...
due to the periodic eddy shedding of the body surface, and then the spatial average pressure \( \Phi(\omega) \) decreases rapidly as the frequency increases. In Figure 5(b), the convection wave number \( K_c \) is almost proportional to the frequency. The convection velocity \( U_c \) of the region can be obtained by calculating the slope. The presence of a noise signal at high frequencies may affect the accuracy of the calculation results.

**Figure 4**: Fluctuation pressure distribution on the body surface

The four parameters of the Corcos model in each region of the vehicle body are calculated separately. The spatial average pressure \( \Phi(\omega) \) and the convection wave number \( K_c \) of the Corcos model in the front side window region are shown in Figure 5. The spatial average pressure \( \Phi(\omega) \) produces a peak at 720Hz due to the periodic eddy shedding of the body surface, and then the spatial average pressure \( \Phi(\omega) \) decreases rapidly as the frequency increases. The convection wave number \( K_c \) is almost proportional to the frequency. The convection velocity \( U_c \) of the region can be obtained by calculating the slope. The presence of a noise signal at high frequencies may affect the accuracy of the calculation results.

**Figure 5**: Corcos model space average pressure \( \Phi(\omega) \) and convection wave number \( K_c \) of front windshield

### 3.2 Sound field components extraction through boundary element method

The sound field component is mainly generated by the periodic detachment of the eddy, thus will be generated around the protruding body of the vehicle body and the irregular parts. Studies have shown that [8], the sound field components produced by the A-pillar and the mirror area contribute the most to the interior of the vehicle, so this paper only considers the sound field components produced by the A-pillar and the rear view mirror. The boundary element model established in VA One is shown in Figure
6. The FSP of the A-pillar and the rear view mirror is used as an excitation to solve the Curle dipole sound source on the surface, and then the Helmholtz acoustic wave equation is used to solve the sound field radiated on the side window due to the pulsating pressure of the A-pillar and the mirror surface. The distribution of the dipole sound source can also be seen from Figure 6, and the sound source intensity is the largest at the base of the rear view mirror and at the transition between the A-pillar and the front fender.

![Figure 6: Boundary element model of A-pillar, rear view mirror and side window](image)

Figure 6: Boundary element model of A-pillar, rear view mirror and side window

Figure 7 shows the root mean square value of A-pillar and mirror pressure space as a function of frequency. It can be seen that the root mean square value of the pressure drops rapidly with the increase of the frequency in the low frequency band, and the pressure from 200 Hz to 2450 Hz has dropped by nearly 50 dB, while the drop above 2450 Hz is very slow, only about 10 dB. It can be seen that most of the energy of the fluctuation pressure is mainly concentrated in the middle and low frequencies.

![Figure 7: Pressure space rms value of A-pillar and rear view mirror (df=22.5Hz)](image)

The FMM (fast multipole method) is used to solve the above boundary element model. Compared with the traditional boundary element method, the FMM solves faster, but the fast boundary element method requires the sound source to be closed. Therefore, some small plates are added during the calculation process. The added plates have no fluctuation pressure and do not participate in the calculation, and has no effect on the solution result. The solution process of the boundary element is relatively slow. After the solution is completed, the SPL of the sound source radiated to the side window can be obtained. The pressure distribution cloud diagram of the side window at different frequencies as determined by the boundary element method is shown in Figure 8.

As can be seen in Figure 8, the sound pressure at the rear view mirror base and the transition region of the A-pillar and the side window is the largest. The pressure is small in the side window region away from the A-pillar and the rear view mirror. At 200 Hz, the maximum sound pressure is large, and then decreases. At 3150 Hz, the sound pressure maximum increases again. The SPL of 1/3 octave of the side window is shown in Figure 9. The side window 1/3 octave SPL gradually decreases at 200-1000 Hz, and...
gradually increases above 1250 Hz. This shows that the energy of the sound field components is mainly concentrated in the high frequency.

![Sound pressure distribution on the side window surface](image)

**Figure 8:** Sound pressure distribution on the side window surface

![1/3 octave SPL of the side window](image)

**Figure 9:** 1/3 octave SPL of the side window

### 4. Result analysis and optimization

#### 4.1 Result analysis

In the wind tunnel test, the flow rate is kept constant, and the gap between the door sheet metal is sealed. Then the SPL of the driver's head cavity is measured. The calculated SPL of the driver's head cavity based on a validated full SEA vehicle model is compared with the test value. The result is shown in Figure 11. As can be seen, the simulated value is close to the test value. Above 500Hz, the simulation value is calculated accurately, which indicates that the method of random modal force coupling DAF has higher accuracy.

In order to optimize the driver's head SPL, the main transmission path to the driver's head cavity can be analysed. The results show that the external excitation from the driver's side window to the inside of the vehicle is the main source of the SPL of the driver's head cavity. The side window can therefore be optimized to reduce the SPL of the driver's head cavity. The SPL of the driver's head cavity is given in Figure 12 for the thickness of the different side window panes. It can be seen that the glass of different thickness has little effect on the SPL of the driver's head cavity below 1600 Hz, while above 1600 Hz, increasing the thickness of the side window glass can significantly reduce the SPL of the driver's head.
cavity. Therefore, increasing the thickness of the side window glass can be used to reduce the SPL of the driver's head cavity in the high frequency band.

![Figure 10: Comparison of simulated and test values](image)

![Figure 11: SPL of the driver's head cavity at different thicknesses of the front side window glass](image)

5. Conclusion

The CFD external flow field simulation model of an EV is established. The Fluent software is used to calculate the pressure distribution of the vehicle under steady state and the fluctuation pressure under transient conditions. Four Corcos model parameters of all surfaces of the vehicle body are extracted in the fluctuation pressure, so as to obtain the convective component in the fluctuation pressure. The boundary element model of the sound field radiated by the rear view mirror to the side window is established, and the sound field component of the side window surface is obtained. The method of coupling random modal force with DAF is used to calculate the SPL of the driver's head acoustic cavity, and the calculation results are compared with the experimental values to verify the accuracy of the method. Finally, the influence of the thickness of different side window glass on the SPL of the driver's head cavity is discussed. The results show that increasing the thickness of the side window glass can be used to reduce the SPL of the driver's head cavity in the high frequency band.

REFERENCES

1 P. Shorter, V. Cotoni, D. Blanchet “Modeling Interior Noise due to Fluctuating Surface Pressures from Exterior flows”, Proc. Society of Automotive Engineers (SAE), ISNVH, June 2012.


ACKNOWLEDGMENTS

The authors would like to thank the following project funding support. This report was prepared as an account of work sponsored by National Key R&D Program of China NumberNo.2017YFB0103204, Shanghai Science and Technology Innovation Action Plan No.18DZ1201703.