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Numerical simulation of in-vehicle sound field under conditions of open or closed car windows

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ABSTRACT

As computation technology develops, sound field numerical simulation in-vehicle has attracted more and more attention. However, it is difficult to simulate sound field in-vehicle at high frequency by using wave-equation-based numerical methods, such as finite element method (FEM), finite difference in time domain (FDTD), etc. To extend the region of effective frequencies, a combined method consisting of finite element method (FEM) and ray-tracking method can be used to simulate the sound field in a car. Even so, the combination of the spectrum at the segmentation frequency between two methods still remains a well-known problem and is worthy of investigating. In this work, only the improved FEM was adopted to simulate the in-vehicle sound field. Through an optimized car model with smoothing fine structures and non-uniform meshing grids, the computation was optimized and the effective frequency was extended up to 4 kHz. Further, sound field distributions under conditions of open or closed lateral front windows (the condition of open windows is approximated by an absorptive boundary) were simulated and analyzed, so as to validate the optimized car calculation model and numerical method.

Keywords: Finite element method, Sound field in-vehicle, Numerical simulation

1. INTRODUCTION

Automotive environment is increasingly becoming an indispensable listening space in our daily life. There are two components of the acoustic environment in the automobile cabin: the noise due to automotive processes or surroundings and the sound field effect produced by the car audio system (1). The acoustic environment in an automobile cabin has a significant effect on the perceived sound quality of the vehicle. In fact, because of the particularity of in-vehicle sound field compared with traditional room sound field, which is caused by a small-size space (2), the research on the sound field in-vehicle still remain to be further developed.

In order to design and predict a better sound reproduction performance inside the car, numerical simulation is a common, low-cost and high-efficiency technical approach. The general numerical simulation methods include ray-traking (RA) (3), finite difference in time domain (FDTD) (4), boundary element method (BEM) (5) and finite element method (FEM) (6). In theory, geometrical acoustics can only be used at frequencies where the wavelength of the sound is considerably smaller than any structure scale in the target acoustic space (7). When the size of reflecting objects become comparable to the wavelength of sound, a wave-based method is predominant. The FEM is attractive because of its inherent accuracy and its ability to handle arbitrary model shape compared with BEM, but it is limited to low frequencies and small rooms due to large computation amount (requiring more memory and computation time) and higher requirements for the finer structures. Therefore, it is necessary to optimize FEM, so that it can be used to simulate the sound field in-vehicle up to higher frequencies.

Actually, FEM has being developed in recent years (8-11). To extend the region of effective frequencies, Aretz used a combined method consisting of finite element method (FEM) and ray-tracking method to simulate the sound field in a car up to 12 kHz, in which the segmentation frequency is approximately 800 Hz (12). Even so, the combination of the spectrum at the segmentation frequency between two methods still remains a well-known problem and is worthy of further

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investigation. In particular, in the context of the rapid development of computer technology, more accurate simulation under shorter computing time can be obtained and thereby guiding the design of sound reproduction.

As mentioned previously, there is a contradiction between improving calculation accuracy (such as extend effective simulation to higher frequencies) and the computation volume (or time cost). There, first, we propose an optimized car model with smoothing fine structures and non-uniform meshing grids, the use of eight-noded cubic volumic element, the computation was optimized and the effective frequency was extended up to 4 kHz, which covers the frequency range of speech. Many factors can contribute to a vehicle's interior sound field. For sound reproduction inside the car, the early reflections caused by the lateral front windows seems to play an important role, owing to their close distance from the ear (13). Therefore, the influence of the lateral front windows on the sound field inside the car was predicted by using the optimized FEM in time domain, which also validate the optimized method. Sound field distribution under two different acoustic boundary conditions, which simulates the lateral front windows being close or open. This work will play an important role in auralization researches in-vehicle.

2. Calculation model

2.1 Mathematical Model

The simulation work in this paper was carried out using the acoustics model in the COMSOL Multiphysics software. The stimulus signal used in this model is time-harmonic, on which the sound propagation in the car cavity can be described by the inhomogeneous Helmholtz equation:

$$\frac{1}{\rho c^2}\cdot\frac{\partial^2 p_t}{\partial t^2}+\nabla\cdot\left(-\frac{1}{\rho}\left(\nabla p_t-\mathbf{q_d}\right)\right)=Q_m, \qquad (1)$$

$$p_t = p + p_b$$

where ρ is the fluid density (SI unit: kg/m^3), c refers to the speed of sound in medium (SI unit: m/s), p_t indicates to the total sound pressure (SI unit: Pa), Q_m denotes as the monopole domain source(SI unit: 1/s^2), $\mathbf{q_d}$ is the dipole domain source (SI unit: N/m^3), p is the sound pressure (SI unit: Pa), and p_b is the pressure of background sound field (SI unit: Pa).

In the finite element domain, the impedance boundary approach ignores possible fluid-structural coupling effects caused by vibration of the car materials. It is assumed that the sound wave propagates only from the direction of the vertical surface. Therefore, the impedance is not affected by the incident sound field, thus can be represented by a constant. Absorption boundary condition can be described by following equation:

$$-\mathbf{n}\cdot\left(-\frac{1}{\rho}\left(\nabla p_t-\mathbf{q_d}\right)\right)=\frac{1}{Z_i}\frac{\partial p_t}{\partial t} \qquad (2)$$

where Z_i is the characteristic acoustic impedance (SI unit: Pa·s/m).

2.2 geometric model

Finite element analysis is a general analysis tool. It is commonly possible to import geometric model data from CAD files. Figure 1 shows the model used in this simulation, which is a simplified model based on the actual size of a real car.The model consists of an enclosed cavity and simplified seat, a point source, s_1, and a receiver point, r_1.

For the purpose of improving the calculation efficiency and ensuring the accuracy, the eight-noded cubic volumic element is used in the calculation (14). In order to ensure the accuracy of the calculation model, the maximum size of the meshing unit should be less than one-sixth of the wavelength. Moreover, for the interior surface of the car with a mutated shape, the mesh near it was refined, and the grid cell size was slightly larger for the continuum in the car cavity. In this way, the interior of the car was divided into many non-uniform grids. Finally, the total number of grid cells is 202117, the largest element size is 0.0274 m, and the minimum element size is 0.00504 m. Such grid cell settings are more than sufficient for calculating the sound field in the time domain within the 4 kHz frequency range.

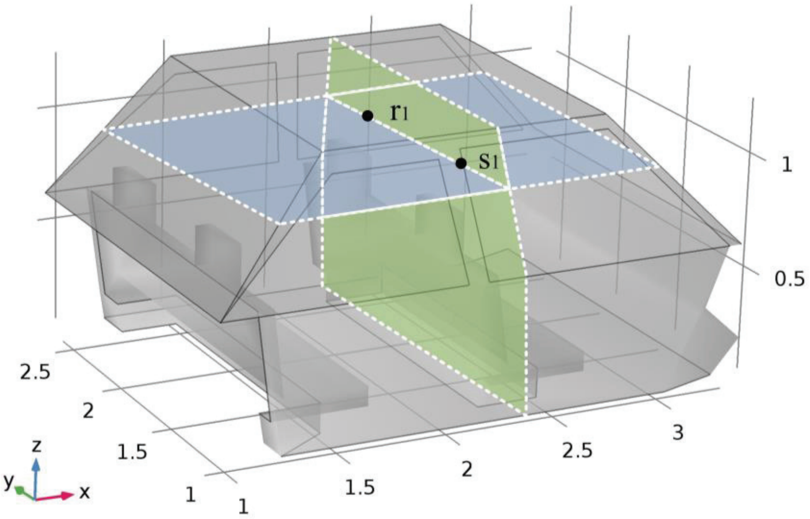

Figure 1-Model of the car cabin and diagram representing x-y (blue) and y-z (green) cross section

2.3 Source and boundary condition

When calculating the impulse response in a car, it is necessary to add an stimulus source for the calculation. In actual measurement, the maximum length sequence (MLS) or the sweep frequency signal is usually used as the excitation sound source to reduce the influence of noise on the measurement result. However, in numerical simulation, because there is no influence of environmental noise, the pulse sound source can be selected as the excitation signal, which makes the calculation simulation more efficient. Gaussian pulses are commonly used signals in time domain simulation. In this paper, Gaussian pulse is used as the excitation sound source for simulation. The time domain expression was as follows:

$$\begin{cases} Q_m = Ae^{-\pi^2 f_0^2 \left(t-t_p\right)^2} \\ t_p - \dfrac{1}{f_0} < t < t_p + \dfrac{1}{f_0} \end{cases}, \tag{3}$$

where A is the amplitude (SI unit: m^2/s), f_0 is the frequency bandwidth (SI unit: Hz), and t_p is the duration of the pulse (SI unit: s), respectively.

Taking into account the computational time that could be limited by computer hardware, the time step Δt was set as 0.125 ms, and the corresponding sampling frequency $1/\Delta t$ was 8 kHz. According to the sampling law (15), the effective frequency that can be accurately calculated under such sampling frequency setting is 4 kHz. The impulse response of the four receiving points can be directly calculated.

When the lateral front windows were close, the impedance boundary conditions of the side windows and the front-rear windscreen were set to 8712 Pa·m/s. However, it is worth mentioning that we replaced the impedance of the front side windows with the impedance of the air, 439.89 Pa·m/*s*, to simulate the boundary condition of lateral front windows that were open, as shown in Table 1. In addition, the impedance conditions of seats and other panels were set as 8852 Pa·m/s, and 3142 Pa·m/s, respectively. The point source and the receiver point located at coordinate (2.4 m, 1.4 m, 1 m) and (2.4 m, 2.2 m, 1 m), respectively, as shown in Figure 1. The heights of the point source and the receiver point are close to the height of the human head when a person is sitting in the car.

Table 1 – The impedance setting of surfaces inside car under two conditions

Impedance (Pa·m/s)	seat	Front-rear windscreen	Rear side windows	Right front side window	left front side window	others
lateral front windows closed	8852	8712	8712	8712	8712	3142
lateral front windows open	8852	8712	8712	439.89	439.89	3142

3. Results and Analysis

The FEM can obtain the numerical solution of each element in the solution domain. In order to predict the effect of the window compartment on the sound field distribution, the sound field distribution in both x-y, y-z cross sections (see Figure 1) along the source point in the coordinate system have been obtained. Then, the sound propagation in cross section in the time-domain under different conditions have been observed, which are shown in Figure 2 and Figure 3, respectively. All these figures illustrate the time domain propagation of sound wave from 0.5 ms to 4.5 ms with 0.5 ms interval.

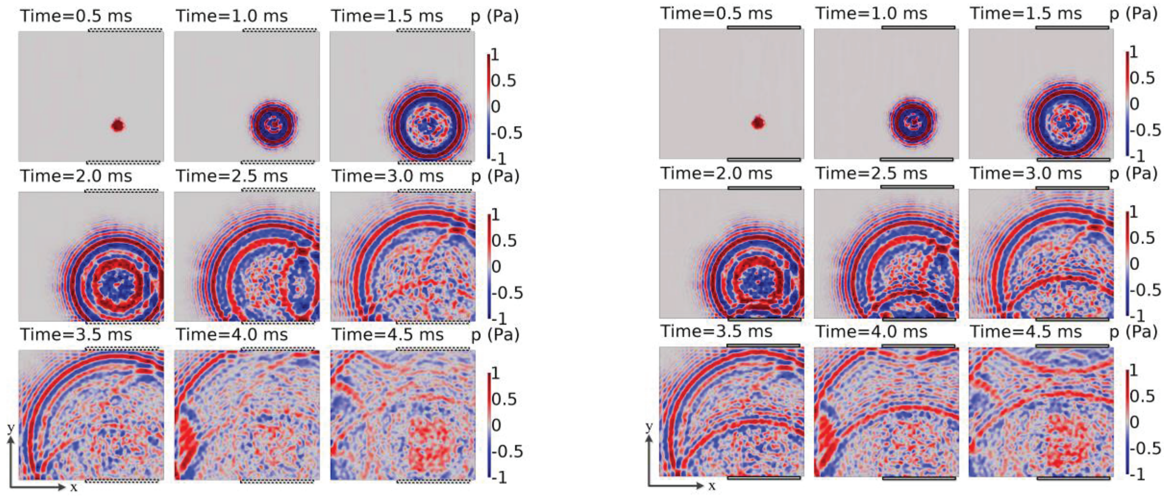

Figure 2- The propagation procedure of sound field on x-y cross section inside car with lateral front windows open (left) and closed (right), where dotted line frames represent open windows while solid line frames represent closed windows

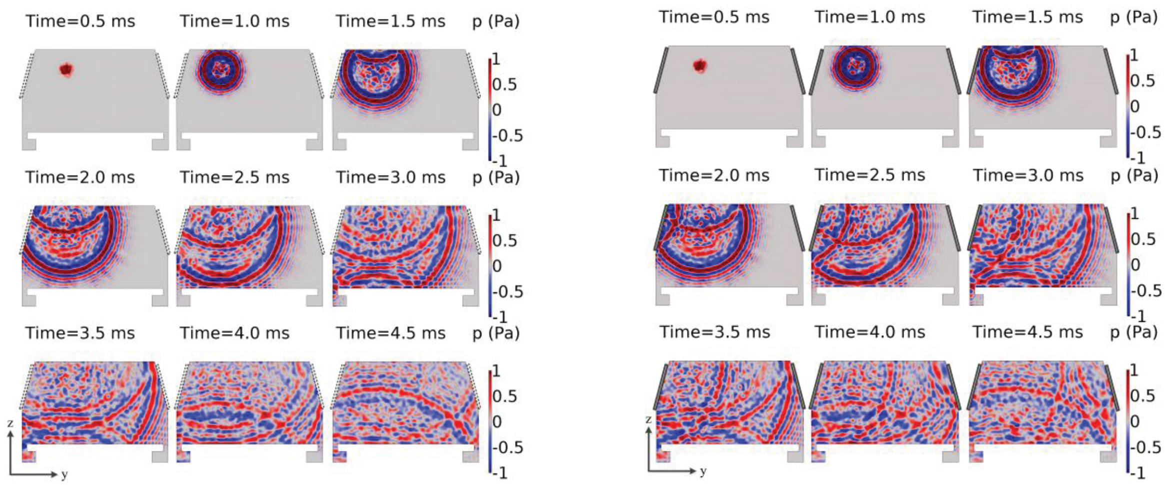

Figure 3-The propagation procedure of sound field on y-z cross section inside car with lateral front windows open (left) and closed (right), where dotted line frames represent open windows while solid line frames represent closed windows

Figure 2 shows the time-domain propagation procedure of sound wave on x-y cross section along source position in car cabin, under the conditions of open and closed lateral front windows. We can see that, will interfere with the direct sound and contribute to the resulting sound field. Due to the small size of car, sound wave can travel to the interface within several millisecond. Therefore, the sound propagation is more strongly influenced by these wave effects. When the lateral front windows are closed, we found that the reflection of the front window smears the time signature of the sound field in the car cabin, just like Figure 2 (right) when the propagation time is more than 2.0 ms.

Similarly, Figure 3 illustrates the time domain diagram of sound wave propagation. When sound propagates to the open window, a significant sound energy leakage can be observed in the figure. Comparing the two groups of time domain propagation figures, when the lateral front windows are closed, that is, when the lateral front window was set as the absorptive boundary, the sound field focusing seems to appear more frequently.

Figure 4 shows the impulse response at receiver point r_1 (in driver seat) under different boundary conditions, namely closed and open lateral front windows. The sound field inside vehicle consists entirely of direct sound and early reflections, which are quickly absorbed or dissipated (the short duration within about 20-30 ms). This is due to the small dimensions of the vehicle interior, namely the emitter is close to reflection/absorption boundary. However, it is difficult to discover the obvious difference between the two impulse responses.

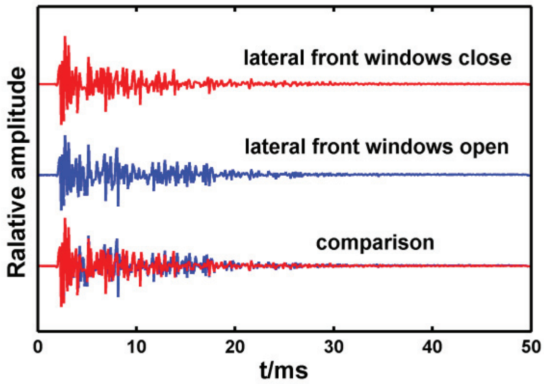

Figure 4- The impulse response in receiver point r1 with lateral front windows closed (blue), open (red) and their waveform comparison

Table 2-The magnitude spectrum statistics in octave of two impulse response at receiver point *r*1

Frequency (Hz)	31.5	63	125	250	500	1000	2000
Magnitude with lateral front windows close	-24.0 dB	-28.2 dB	-19.8 dB	-18.0 dB	-16.9 dB	-5.3 dB	0 dB
Magnitude with lateral front windows open	-29.0 dB	-32.3 dB	-21.2 dB	-18.5 dB	-17.5 dB	-6.9 dB	0 dB
The magnitude difference	5.0 dB	4.1 dB	1.4 dB	0.5 dB	1.0 dB	1.6 dB	0 dB

Further, the magnitude spectrum statistics in octave of the two impulse responses can be got with dirac software, as shown in the Table 2. it can be found that the magnitude of the spectral intensity under the condition of lateral front windows open is generally lower than that of windows close, due to the sound energy leakage. Moreover, it's worth noting that there is more significant difference in low frequencies, which indicates that the sound energy leakage mainly occurs in low frequencies.

For a typical vehicle, the decay time for a 60 dB signal reduction is 30 to 50 ms. Therefore, reverberant field cannot form in the environment of this size, whose reverberation time is tremendously small. This reason could be that the sound path between two reflectors is short, that is say, the sound wave can frequently reach the absorptive boundaries, and thus the sound the energy is quickly absorbed by the sound absorptive boundary. Because the absorption interface absorbs more high-frequency sound, the sound wave in the car attenuates faster at high frequency, so that the reflection times are less when the sound wave propagates in the car. On the other hand, the frequency of low-frequency reflection is more, so after the low-frequency energy leakage caused by window opening, the energy statistics will be less.

4. CONCLUSIONS

This work aims to design a finite element model with simplified car interior, which is applied to high frequency in order to investigate how sound propagate inside car cabin with the influence of lateral front windows. Through an optimized car model that combines the used of eight-node cubic volumic element, smoothing fine structures and non-uniform meshing grids, the calculating procedure was optimized and the effective calculation frequency was extended up to 4 kHz, which covers the frequency range of speech. The influence of the lateral front windows on the sound field distribution inside the car has been analyzed. We obtained the time domain variation figures of the sound field propagation on different cross sections of the vehicle with the setting of the Gaussian pulse point sound source. Results show that, in general, most of the energy of sound field inside the car is concentrated in direct sound and early reflection. Sound waves can be attenuated quickly in the car, which can be attributed to the smaller size of the car. The closing or opening of the window has a significant effect on the reflection and absorption of sound waves in the vehicle. Incontestable, the opening and closing of the window has a great influence in the distribution of the sound field in the car, which is manifested in the more frequent sound focusing when the windows are closed and the greater influence of the low-frequency energy attenuation when the windows are opened. It can be found that the setting of the side window is indispensable when we study the sound field in the car.

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