The Sound Field Characteristics in Automobile under Different Speaker Height based on Numerical Simulation

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Abstract. The automotive acoustic environment has become an indispensable listening space in people’s daily lives. However, due to the complexity of the acoustic environment inside automobiles, the sound reproduction in automobile is particularly problematic compared with that in ordinary domestic environments. From the perspective of sound reproduction, it is an effective approach to improve the reproduction performance by raising the speaker height such that nearer to the height of listener’s ear. However, this issue has been less studied quantitatively. In current work, we aim to explore how the speaker height affects the sound field characteristics at target listening region by using the finite element method. The speakers at front door inner panels were mounted to three different heights, respectively, and the sound field characteristics at target listening region in driver seat were analysed. Result showed that for higher speaker layout resulted in larger sound pressure levels at the target listening point, and the sound field distribution tends to be more homogeneous. Also, raising the speaker height is conducive to giving a constant frequency response at the target listening point. This works can provide the reference for the design of automotive audio system.

1. Introduction
Automotive environment is increasingly becoming an indispensable listening space in our daily life. The application of sound reproduction in automobile is becoming more and more common. However, the acoustic environment in the automobile is different from the ordinary domestic reproduction environment. In practice, the acoustic environment inside automobiles is complex and with dense acoustic modes at low frequencies and rapid attenuation at high frequencies, because of the small acoustic space with complicated interior reflection boundaries, the irregular interior materials with different sound-absorption coefficients, and the effect of seat occlusions on sound propagation between the front and rear seats [1, 2]. Therefore, the sound reproduction inside an automobile is particularly problematic compared with that in ordinary domestic reproduction environment [3], and remain to be further developed.

From the perspective of acoustics, it is not suitable for high-quality sound reproduction in automobile [3]. However, in practical application, sound reproduction needs to be carried out in the automotive environment. Therefore, special acoustic design and audio signal processing are needed to reduce some reproducing defects in audio systems, including narrow listening region, sound image direction distortion, timbre change in reproduction, thereby improve reproduction performance. The
typical basic installation involves speakers mounted in the doors, and the sound tends to come from low down in the automobile, its frequency response being quite badly affected by the location [3, 4].

To improve the quality, we tend to mount some higher-frequency units nearer to ear height, often being a couple of tweeters mounted in the dashboard [3]. This can dramatically improve the sound quality and intelligibility, and brings the sound image upwards. Thus, raising the speaker height to ear height is a common and effective approach to reduce sound image direction distortion, enlarge listening region in automotive sound reproduction. However, the existing research usually stays in the stage of perception and psychoacoustics, and there is still a lack of quantitative research [3, 4]. This motivates us to explore systematically how the speaker height influence the sound field characteristics at target listening region in current work.

To explore the influence of the speaker height on the sound field characteristics at a certain listening region, the numerical simulation is a common, low-cost and high-efficiency technical approach. The common numerical simulation methods include ray-tracing [5], finite element method (FEM) [6-8], boundary element method (BEM) [9] and finite difference in time domain (FDTD) [10].

In theory, geometrical acoustics can only be used in mid to high frequency domain, i.e., when wave length of sound is smaller than the physical dimension of reflection surface in the room, where the propagation of sound wave can be regarded as the sound energy along the sound ray or particle by using the concept of light in geometric optics, namely ignores the wave properties of sound, such as some wave effects of standing waves, diffraction and interference [5]. When the size of reflecting objects become comparable to the wavelength of sound, i.e., in low frequency domain, a wave-based method is predominant [6-8]. From the perspective of sound reproduction, the sounds in low to mid frequency domain are important to the perceived sound quality. Because each element has its own shape and can be connected with other elements in different ways, FEM is better for solving an acoustic problem with a complex boundary shape, such as the sound field inside an automobile, compared to the BEM [6]. Thus, the FEM simulation was adopted in current work.

In this paper, based on the FEM simulation, the sound pressures (at frequencies of 20 Hz to 1000 Hz with interval of 5 Hz) at the listening region in driver seat were simulated with COMSOL Multiphysics software, and then employed to explore the influence of the speaker height on the sound field characteristics at the listening region. The three dimension (3D) geometric model of a real automobile was generated with a 3D laser scanner. The speaker was set as a simplified model of circular membrane with unit inward normal acceleration. The absorption coefficients of interior boundaries were measured with the reverberation room method. Finally, the frequency response at the target listening point in driver seat as well as the spatial distribution of the sound pressure level (SPL) in the listening region near target listening point were analysed.

2. Numerical Simulation

2.1. Mathematical Model

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

\[
\nabla \left( -\frac{1}{\rho} \nabla p_t - q_d \right) - \frac{k^2}{\rho} p_t = Q_m, \tag{1}
\]

where \( \rho \) is the fluid density (SI unit: kg/m\(^3\)), \( k \) refers to the wave number (SI unit: 1/m), \( p_t \) indicates to the total sound pressure (SI unit: Pa), \( Q_m \) denotes as the monopole source (SI unit: 1/s\(^2\)), \( q_d \) is the dipole 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).

Generally, the boundary condition for FEM is directly given by the complex impedance, which
encompasses the attenuation (i.e., the reduction of the amplitude of the sound pressure) and phase characteristics (i.e., the influence of the phase of the sound pressure). However, for convenience, the boundary condition in FEM can also be expressed using the absorption coefficients. The impedance \( Z_i \) (SI unit: Pa·s/m) without phase can be expressed using the absorption coefficient \( \alpha_n \) as follows:

\[
Z_i = \rho c \frac{1 + R}{1 - R} \left( 1 + \frac{i \alpha_n}{Z_i} \right) \cdot \frac{1}{\frac{1}{Z_i} - \frac{1}{\rho} \nabla p_t - q_d} = -\frac{i \omega}{Z_i} p_t
\]

\[
R = e^{i \phi} \sqrt{1 - \alpha_n}. \tag{2}
\]

2.2. Geometrical Model and Boundaries Conditions
The 3D geometrical model of an automobile cabin (FAW Zastava HS7) was produced using a laser scanner (UniSCAN) as shown in figure 1(a). The model was then imported into the simulation software. Further details of the scanning and modelling can be found in Ref. [11]. The target listening point was set at the driver’s seat with height of 0.8 m (i.e., with vertical distance of 0.8 m from the point to the bottom of the automobile), indicating the centre of the driver’s head. Two circular membranes with diameter of 3 inch were set on front door panels with different height [with vertical distance of 0.1 m (n = 1), 0.3 m (n = 2) and 0.5 m (n = 3) from the centre of the membrane to the bottom of the automobile] [see figure 1(c)]. As shown in figure 1(b), there are two rectangular planes (0.7 m × 0.55 m × 0.45 m) near the target listening point, representing the horizontal and median listening regions respectively. Figure 2 shows the absorption coefficients for the interior boundaries of an automobile for different frequencies. These absorption coefficients were measured with the reverberation room method. According to the literature [12], we treat the glass as an acoustic hard boundary.

Figure 1. 3D geometrical models for FEM numerical simulation. (a) The shape of scanned automobile; (b) the interior structure and the planes representing listening region; (c) the circular membranes with different heights.

Figure 2. Absorption coefficients for the interior boundaries of the automobile.
2.3. **FEM simulation**

In the FEM simulation, the source excitation for two circular membranes was an inward normal acceleration with \( a = 1 \text{ m/s}^2 \). The sound fields for different speaker heights were studied through parametric scanning settings in the software. The frequencies of the source varied from 20 Hz to 1 kHz with interval of 5 Hz. For the accuracy of simulation, the maximum element size should be less than \( 1/5 \) of the wavelength \([6, 12]\). Thus, to simulate the sound field below 1 kHz accurately, the size of the elements should be less than 6.86 cm. Therefore, we used a non-uniform free tetrahedral mesh with a maximum size of 67 mm and a minimum size of 6 mm [figure 3(a)]. In particular, to analyse the geometry of the circular membranes with a sufficiently fine grid, the maximum size of the local grid element of the circular membranes was set to 5 mm, as shown in figure 3(b). The total number of elements was 327320.

![Figure 3. The non-uniform free tetrahedral mesh settings.](image)

3. **Result and Analysis**

Figure 4 plots the SPL distribution at frequencies of 50 Hz, 500 Hz and 1000 Hz at the x-y cross section (with vertical distance of 0.8 m from the plane to the bottom of the automobile) under different speaker heights \((n = 1, 2 \text{ and } 3)\). Note that, at the frequency of 50 Hz, the SPL distribution in x-y cross section tends to be uniform regardless of speaker heights. This is because there is the pressure region at low frequencies where the wavelength of sound is much longer than the size of the listening space [3]. At frequencies of 500 Hz and 1000 Hz, it presents an obvious modal phenomenon. As can be seen in figure 4, the SPLs are higher and the SPL distribution tends to be more uniform for larger speaker height, especially for 500 Hz and 1000 Hz.

![Figure 4. The SPL distribution in the x-y cross section at the height of the target listening point in driver’s seat at frequencies of 50 Hz, 500 Hz and 1000 Hz, under different speaker heights \((n = 1, 2 \text{ and } 3)\).](image)
Figure 5 shows the frequency response at target listening point under different speaker heights. Note that, there are obvious peaks and valleys in the frequency response below 1000 Hz, which is due to the degeneracy of each resonant mode. When the wavelength of the low-frequency sound wave and the physical dimensions of the automobile are comparable, the sound reflects from the boundaries of the automobile form various resonance modes that strengthen the response significantly at some frequencies [6, 13]. Additionally, it seems that the SPL variation with frequency is smaller when \( n = 3 \) (i.e., at speaker height of 0.5 m). This shows that raising the speaker height is conducive to give a constant frequency response at the target listening point.

Figure 6 plots the means and standard deviations of SPL for different sample points on the horizontal and median listening regions. After raising the speaker height, the average SPL increases, but the variation of the standard deviations (SD) is subtle, in both horizontal and median plane. For instance, the SPL increase by more than 4 dB for speaker height of 0.3 m \( (n = 2) \) compared with that for speaker height of 0.1 m \( (n = 1) \). In horizontal plane, it seems that the SD of SPL is smallest when the speaker height is 0.3 m, which indicates that the uniformity of sound field near the target listening point on the horizontal plane is the best.

4. Conclusions
In current work, we aim to explore how the speaker height affect the sound field at driver’s seat, an FEM simulation was presented in present work. The FEM was used for frequencies from 20 Hz to
1000 Hz with the interval of 5 Hz. The SPL distribution and frequency response at the target listening point in driver’s seat were analysed. Results showed that the sound pressure levels are higher and the sound field distribution tends to be more uniform for larger speaker height. Also, raising the speaker height is conducive to give a constant frequency response at the listening point. This paper can provide reference values for the design of the automotive audio systems, e.g., advising that raising speaker height can improve the frequency response and give an uniform sound field distribution at listener position.

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