The Influence of Seat Occlusion on Driver’s Binaural Signal in Automobile based on FEM-RTM Simulation

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Abstract. Automotive environment is increasingly becoming an indispensable listening space in our daily life. Affected by the seat occlusions on sound propagation between the front-row and rear-row space, the speech communication between front and rear passengers in automobile is a well-known problem. However, this issue has been paid less attention. To this issue, the numerical simulation is a common, low-cost and high-efficiency technical approach. However, it is a well-known limitation on the effective frequencies to common numerical methods. To extend the region of effective frequencies, a combined approach of the finite element method (FEM) for low-frequency and the ray-tracing method (RTM) for high-frequency (i.e., FEM-RTM) was adopted in current work. The full-bandwidth binaural room impulse responses for a listener in driver’s seat were simulated with the speaker at mid-right seat, and both conditions with seats and without seats were taken into account. Result showed that the seats occlusions mainly affected the left ear (i.e., contralateral ear). The seat occlusions reduced the early decay time, speech transmission index and magnitude spectrum for left ear considerably. The inter-aural correlation coefficient under condition without seats was lower than that under condition with seats.

1. Introduction
The automotive acoustic environment has become an indispensable listening space in people’s daily lives. However, 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 field characteristic inside an automobile is particularly problematic compared with that in traditional indoor environments, and remain to be further developed.

In particular, the seat occlusions, which affect the sound propagation from the speaker to the listener’s ears, significantly affects the sound received by listeners in front seat inside an automobile [3-5]. Parizet [3] demonstrated that there is a loss in the transmission of speech from the front speaker to the rear listeners because the cabin is separated into two compartments by the seat. Additionally, Visintainer and VanBuskirk [4] also reported that the seats are the major contributor to the interior sound absorption inside an automobile, providing the greatest reduction in interior sound level. These occlusions significantly reduce the speech intelligibility, especially when someone in the front seat is
listening to passengers in the rear [5, 6]. This motivates us to explore systematically how the seat occlusions influenced the sound propagation between the front and rear seats.

In comparison to the actual measurement, the numerical simulation is a common, low-cost and high-efficiency technical approach. The commonly used numerical methods can be divided into two categories, i.e., geometrical acoustics (GA) method and wave-based method. In the mid to high frequency domain, or when wave length of sound is smaller than the physical dimension of reflection surface in the room, 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 etc [7]. Common implementations of the GA include the image source method and the ray-tracing method (RTM) [8]. In general, the GA method is only applicable in the frequency domain that higher than the Schroeder frequency [9]. In the frequency domain that lower than Schroeder frequency, the wav-based numerical method, such as finite element method (FEM) [10-12], boundary element method (BEM) [13] and finite difference in time domain [14], is exactly an applicable approach. 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 [10]. It is obvious that both the GA method and the wave-based method have their own advantage in applicable frequency domain. In order to integrate the advantages of the two methods, the FEM-GA combined approach to realistic full bandwidth simulation in small space, such as automobile space, has been developed by Aretz and Vorländer [15, 16]. In their works, the FEM was used when the frequency is lower than the Schroeder frequency, and the image source method was used for frequencies higher than the Schroeder frequency. While the image source method considers the reflecting interface as equivalent image sound sources to determine the path of reflected sound, thus it is only useful for rectangular rooms with a simple boundary, but it is not suitable for an automobile interior, which has an irregular shape and a complex boundary [8]. Compared with the image source method, the RTM considers diffuse reflections from surfaces. It is better for automotive environments with complex boundaries [8]. Thus, the combined of the FEM and RTM simulation, i.e., FEM-RTM simulation, is more appropriate for the full-bandwidth simulation in automobile, thereby is adopted in current works.

In this paper, based on the FEM-RTM combined approach, the full bandwidth binaural room impulse responses (BRIRs) in automobile were simulated with the COMSOL Multiphysics software, and then employed to explore the influence of seat occlusions on the sound received by driver. First, three-dimensional (3D) geometric models of a real automobile and a virtual listener [a Knowles Electronic Manikin for Acoustic Research (KEMAR)], including the head and torso, were produced with a 3D laser scanner. The virtual listener was in the driver’s seat, and the speaker was in the mid-right seat. The absorption coefficients of interior boundaries were measured with the reverberation room method. We then obtained the full-bandwidth BRIRs at the receiver points (i.e., KEMAR’s ear canals) under conditions with seats and without seats. Based on these BRIRs, the magnitude spectrum and room acoustical parameters such as the early decay time (EDT), speech transmission index (STI) and inter-aural correlation coefficient (IACC) were analysed.

2. Numerical Simulation

2.1. Geometrical Model and Boundary Conditions

Both the FEM and RTM simulations were conducted using the software COMSOL Multiphysics. First, 3D geometrical models of an automobile cabin (FAW Zastava HS7) and KEMAR were produced using a laser scanner (UniSCAN), as shown in figure 1. These models were then imported into the simulation software. Further details of the scanning and modelling can be found in Ref. [17]. Figure 2 shows the measured absorption coefficients for the interior boundaries of an automobile for different frequencies. These coefficients were used in both the FEM and RTM simulations. These absorption coefficients were measured with the reverberation room method. According to the literature [15], we
treat the glass as an acoustic hard boundary except for the lowest frequency bands. Generally, the boundary condition for FEM is directly given by the complex impedance, which encompasses the attenuation and phase characteristics [15]. However, for convenience, the boundary conditions for the FEM simulation in present work were expressed using the absorption coefficients in line with the RTM simulation.

**Figure 1.** 3D geometrical models for numerical simulation, integrated with a Knowles Electronic Manikin for Acoustic Research (KEMAR), including the conditions with seats (left) and without seats (right).

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

### 2.2. FEM-RTM simulation

We used acoustic reciprocity, i.e., when the sound wave is generated by a point source and propagates to the left or right ear, the sound pressure received at the target ear is equivalent to the sound pressure obtained by exchanging the position of the source and the receiver. The listener (KEMAR) was in the driver’s seat, and the speaker (i.e., receiver point) was on the mid-right seat, as shown in figure 1. The receiver points (i.e., point sources) were on the KEMAR’s ear canals.

In the FEM simulation, the source excitation was a flow with $Q = 1 \text{ m}^3 \text{s}^{-1}$. The frequency of the source was varied from 2 Hz to 1 kHz with interval of 2 Hz. For the accuracy of simulation, the maximum element size should be less than 1/5 of the wavelength [10, 15]. 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 6.7 cm and a minimum size of 0.6 cm. The smaller elements were used to model the details of the listener’s auricles. The total number of elements was approximately 245746 for condition with seats and 265772 for without seats. The FEM simulation gives the complex sound pressure below 1 kHz, which is far below the Nyquist frequency of 22.5 kHz when sampling at 44.1 kHz. Other researchers commonly extend the frequency range to the Nyquist frequency by padding the missing frequency domain with zeros [18]. However, this method does not consider the Gibbs effect. In other words, there will be serious pre-ringing in a time-domain pulse. To avoid this, we used a cosine window function to add the missing frequency domain [19].
In the RTM simulation, the speaker is simplified as an omnidirectional point source emitting 7000 rays each with a strength of 0.03 W. We used the center frequencies of the one sixth octaves, which range from 500 Hz to 20 kHz. The result is extended to the Nyquist frequency with Kaiser–Bessel window functions [20], and then converted to BRIRs in the time domain. Each ray contributes an amplitude, arrival time, and frequency to the time-domain signal. Thus, the BRIR of a source–receiver configuration can be determined. The result is a time-domain pulse with a length of 35 ms and a sampling frequency of 44.1 kHz. At this length, the attenuation of the pulse is completely retained, and the computation time can be reduced as much as possible. In addition, extra time steps are used to give a more precise evaluation of the arrival times. To meet the requirements of the combination at high and low frequencies, the BRIRs need to be zeroed to 4096 sampling points.

The amplitude of the spectrum obtained by FEM needs to be consistent with that of RTM in the transition frequency domain. Therefore, we calculated the average energy for both FEM and RTM results in the transition frequency band, which ranges from 500 Hz to 1 kHz. The coefficient of proportionality for the average energy of the FEM and RTM results was used as the amplitude normalization coefficient for the FEM results. Finally, BRIRs were obtained in the time domain by an inverse Fourier transform, and the arrival times were adjusted so that they were consistent with the RTM results. The combined method simply adds the BRIRs from the FEM and RTM simulations after filtering. A low-pass filter with an upper frequency of 800 Hz is used for the BRIRs from the FEM simulation and a high-pass filter with a lower frequency of 800 Hz is used for the BRIRs from the RTM simulation. A Butterworth zero-phase filter of order 8 is used for the low- and high-pass filtering. It can perform cross-fading well without adding a frequency-dependent latency, which would result in a delay for the BRIRs.

3. Result and Analysis

As an example, the FEM or RTM results after filtering and the combined result are shown in figure 3. As can be seen, the BRIRs obtained by the two methods can combined with good continuity at the transition frequency 800 Hz. Note that since the frequency component of FEM result is less than RTM result, the amplitude of its impulse response in time domain is much smaller than that for RTM result.

Figure 3. Result from the finite element method (FEM), ray-tracing method (RTM), and the FEM-RTM combined results in (a) time and (b) frequency domains.

Figure 4 plots the curve of energy decay [21] and the magnitude spectrum for the BRIRs at both ears under the conditions with or without seats. Also, according to the ISO 3382-2-2008 [22] and IEC 60268-16 [23], the EDT, STI and the magnitude at seven octave bands are shown in table 1. As can be observed in figure 4(a), under the condition with seats, the total energy of the BRIR at right ear is much higher than that at left ear, with difference near 10 dB (also see table 1). However, the difference between the total energy of BRIRs at two ears is subtle under the condition without seats. On the one hand, since the speaker is in mid-back seat is in the contralateral side, the head shadow may result in a sound energy that is higher at one ear than the other [5, 24]. On the other hand, the diffraction and
reflection of sound from very close boundaries (e.g., from the left front window) compensate for the adverse occlusions and head shadow in the sound energy, while the sound waves propagating from the speaker to the effective reflectors is seriously blocked by the seats under condition with seats [5]. For these reasons, it is expected that the energy difference of BRIRs between two ears under the condition without seats is much lower than that under the condition with seats.

**Figure 4.** Curves of the energy decay (a) and the magnitude spectrum (b) of the BRIRs from the FEM-RTM simulation.

**Table 1.** The room acoustical parameters under conditions with or without seats.

| Condition      | Frequency (Hz) | Par. | 125 | 250 | 500 | 1k  | 2k  | 4k  | 8k  | overall |
|----------------|----------------|------|-----|-----|-----|-----|-----|-----|-----|---------|
| Left ear       |                | EDT/s| 0.13| 0.04| 0.07| 0.1 | 0.18| 0.01| 0   | 0.1     |
|                |                | STI  | 0   | 0   | 0   | 0   | 0   | 0   | 0   | 0.59    |
|                |                | Mag./dB| -25.6| -16.9| -17.8| -10.5| -6  | -2.8| 0   | -43     |
|                |                | EDT/s| 0.16| 0.14| 0.12| 0.1 | 0.06| 0.05| 0.02| 0.12    |
|                |                | STI  | 0   | 0   | 0   | 0   | 0   | 0   | 0   | 0.75    |
|                |                | Mag./dB| -34.1| -26.5| -26.7| -16.7| -7.8| -3.7| 0   | -33.7   |
| Right ear      |                | EDT/s| 0.1 | 0.07| 0.07| 0.05| 0.12| 0.23| 0.19| 0.08    |
|                |                | STI  | 0   | 0   | 0   | 0   | 0   | 0   | 0   | 0.73    |
|                |                | Mag./dB| -35.3| -28.7| -23.7| -8.6 | -6.8| -3  | 0   | -34     |
|                |                | EDT/s| 0.12| 0.11| 0.08| 0.11| 0.16| 0.14| 0.18| 0.11    |
|                |                | STI  | 0   | 0   | 0   | 0   | 0   | 0   | 0   | 0.78    |
|                |                | Mag./dB| -34.1| -28.2| -18.4| -11.5| -6.8| -3.7| 0   | -33.5   |

Note that, the magnitude of the BRIRs at right ear was little affected by the seat occlusions, except for octave band of 500 Hz, as shown in figure 4 and table 1. For the left ear, the low-frequency components are mainly affected. This may be because the seats change the spatial distribution of low-frequency standing waves inside automobile [1, 2]. Accordingly, the STI of left ear under the condition without seats is enhanced by 0.16 compared with that under the condition with seats, while the STI of right ear is enhanced by 0.05 (see table 1). When the seats are removed, the EDTs for left ear in octave band higher than 500 Hz decrease, while the EDTs for right ear in each octave bands increase. Also, we found that the IACC under condition without seats (0.18) was lower than that under condition with seats (0.28).

4. Conclusions

To explore how the seat occlusions affect the sound propagation from the rear-row speaker to the front-row listener’s ears, a full-bandwidth numerical simulation (i.e., FEM-RTM combined method) was exhibited in present work. The FEM was used for frequencies below 800 Hz, and the RTM method was used for frequencies above 800 Hz. Based on the FEM-RTM combined method, the full-bandwidth BRIRs under conditions with or without seats were simulated, and then used to analyse the magnitude spectrum and room acoustical parameters such as EDT, STI and IACC. Result showed that
the seats occlusions mainly affected the binaural signal of the left ear (i.e., contralateral ear) rather than the right ear. The seat occlusions reduced the EDT, STI and magnitude spectrum for left ear considerably. When the seats are removed, the IACC also decreased. It seems that the seats occlusions significantly influenced the sound received by driver. This paper can provide reference value for interior acoustic design inside automobile, e.g., advising that we should reduce the occlusions from seats between the front and rear rows to ensure an efficient and clear communication.

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