ICSV14
Cairns • Australia
9-12 July, 2007

14th International Congress on Sound & Vibration

RESEARCH OF AURALIZATION IN SMALL ENCLOSURES

Fangli Ning[1], Geng Liu[1] and Juan Wei[2]

College of Mechanical and Electrical Engineering, Northwestern Polytechnical University
Xi'an, P.R. China
[2] State Key Lab.of Integrated Service Networks, Xidian University
Xi'an, P.R. China
ningfl@nwpu.edu.cn

Abstract

Auralization is front edge research in architectural acoustics. In real life, human main living areas are Small enclosures, such as living room, work room, car cab, ect. Because of wavelength of sound in low frequency being close to dimensions of small enclosures, scattering and diffraction in the course of sound radiation couldn't be ignored. As a result, auralization based on geometrical acoustics can't be applied in small enclosures. In this paper, firstly, based on Helmholtz equation and its boundary equations, model of Finite Element Method (FEM) is given for computing low frequency sound transfer function in small enclosures. Secondly, procedures for the realization of auralization software in small enclosures are presented in detail. Lastly, as an example, the auralization is realized in one car cab model.

1. INTRODUCTION

Auralization is front edge research in architectural acoustics. Major aim of auralization is to rebuild sound field and simulate sound in enclosures. With auralization, audience could perceive the interior sound effect before enclosures are completed. Now, full digital auralization is the focal point of auralization [1]. All procedures of full digital auralization is completed by software. Several companies have developed their own full digital auralization software [2, 3].

In real life, human main living areas areSmall enclosures, such as living room, work room, car cab[4], ect. Because of wavelength of sound in low frequency being close to dimensions of small enclosures, scattering and diffraction in the course of sound radiation couldn't be ignored. As a result, auralization based on geometrical acoustics can't be applied in small enclosures [4, 5].

In this paper, firstly, based on Helmholtz equation and its boundary equations, Finite Element Method (FEM) model is given for computing low frequency sound transfer function in small enclosures. Secondly, processing method for binaural characteristic is put forward. Lastly, procedures for the realization of auralization software in small enclosures are presented in detail. As an example, the auralization is realized in one car cab model.

2. FEM MODEL AND SOUND TRANSFER FUNCTION

Assuming that there has a sound source, which provides media mass of unit volume $\rho_0 q(\vec{r},t)$in unit time. Then using wave equation about sound pressure $p(\vec{r},t)$, the sound field situation of small enclosures can be expressed as:

$$\nabla^2 p - \frac{1}{{c_0}^2}\frac{\partial^2 p}{\partial t^2} = -\rho_0 \frac{\partial q}{\partial t} \tag{1}$$

Where c_0 is transmitting velocity of sound in air, ρ_0 is air density.

If sound source makes harmonic vibration, the function of sound source $q(\vec{r},t)$ is written as:

$$q(\vec{r},t) = q_0(\vec{r})\mathrm{e}^{\mathrm{j}\omega t} \tag{2}$$

Where ω is frequency.

Due to the system considered is linear, and then sound pressure in each point of small enclosure vibrates with frequency of sound source. Sound pressure is given as

$$p(\vec{r},t) = p(\vec{r},\omega)\mathrm{e}^{\mathrm{j}\omega t} \tag{3}$$

Substituting equations(2) and (3)into(1), equation (1) can be written as Helmholtz equation:

$$\nabla^2 p_\omega(\vec{r}) + \left(\frac{\omega}{c_0}\right)^2 p_\omega(\vec{r}) = -\mathrm{j}\rho_0\omega q_\omega(\vec{r}) \tag{4}$$

After that, the question in time domain can be transferred into frequency domain. At the same time, equation (4) is also the control equation of building FEM equation. In order to simplify the writing, let: $p = p_\omega(\vec{r})$, $f = -\mathrm{j}\rho_0\omega q_\omega(\vec{r})$. Then, Helmholtz equation is simplified as

$$\nabla^2 p + k^2 p = f \tag{5}$$

In our research, two kinds of boundaries, rigid and absorption walls, are taken into account. S_1 is rigid wall, and S_2 is absorption wall. Boundary conditions are given as

$$\frac{\partial p}{\partial n} = 0 \qquad \text{On } S_1 \tag{6}$$

$$\frac{\partial p}{\partial n} = -\mathrm{j}\rho\omega\frac{p}{z_s} \quad \text{On } S_2 \tag{7}$$

Where n is direction of outward normal to the wall, z_s is sound impedance of absorption wall S2

Using variation principle based on equation(5), (6)and(7). Element's FEM equation can be written as:

$$\mathbf{K}^{(e)}\mathbf{p}^{(e)} + \mathrm{j}\rho\omega\mathbf{C}^{(e)}\mathbf{p}^{(e)} - k^2\mathbf{M}^{(e)}\mathbf{p}^{(e)} = \mathbf{F}^{(e)} \tag{8}$$

Where local matrixes are:

$$\begin{aligned}
\mathbf{K}^{(e)} &= \int_{v^{(e)}} (\nabla\mathbf{N})(\nabla\mathbf{N})^T dV \\
\mathbf{M}^{(e)} &= \int_{v^{(e)}} \mathbf{N}\mathbf{N}^T dV \\
\mathbf{C}^{(e)} &= \int_{s_2^{(e)}} \mathbf{N}\mathbf{N}^T / z_s dS \\
\mathbf{F}^{(e)} &= \int_{v^{(e)}} f\mathbf{N} dV
\end{aligned} \tag{9}$$

Where $\mathbf{N}$ is column vector of element shape function, $\nabla\mathbf{N}$ is derivative matrix of $\mathbf{N}$

According to rule of elements' combination, system global matrixes are given as:

$$\mathbf{M} = \sum_e \mathbf{M}^{(e)}\ , \quad \mathbf{K} = \sum_e \mathbf{K}^{(e)}$$
$$\mathbf{C} = \sum_e \mathbf{C}^{(e)}\ , \quad \mathbf{F} = \sum_e \mathbf{F}^{(e)} \tag{10}$$

Then, system global FEM equation in small enclosures is given as:

$$\left(\mathbf{K} + \mathrm{j}\rho\omega\mathbf{C} - k^2\mathbf{M}\right)\mathbf{p} = \mathbf{F} \tag{11}$$

When sound source is point source and locates at position $\vec{r}_0$, source function $q_\omega(\vec{r})$ is:

$$q_\omega(\vec{r}) = q_\omega(\vec{r})\delta(\vec{r} - \vec{r}_0) \tag{12}$$

Where，delta function is $\delta(\vec{r} - \vec{r}_0) = \begin{cases} 0 & \vec{r} \neq \vec{r}_0 \\ 1 & \vec{r} = \vec{r}_0 \end{cases}$

Substituting equation (12) into (9):

$$\begin{aligned} \{F\}^{(e)} &= \int_{V^{(e)}} f(\vec{r})\{N\}dV \\ &= \int_{V^{(e)}} - j\rho_0\omega q_\omega(\vec{r})\{N\}dV \\ &= \int_{V^{(e)}} - j\rho_0\omega q_\omega(\vec{r})\delta(r - r_0)\{N\}dV \\ &= - j\rho_0\omega q_\omega(\vec{r}_0)dV\{N\}\Big|_{r=r_0} \end{aligned} \tag{13}$$

Let $Q_0 = q_\omega(\vec{r}_0)dV$, Q_0 is volume velocity of sound source. Equation (13) can be written as:

$$\{F\}^{(e)} = - j\rho_0\omega Q_0\{N\}\Big|_{r=r_0} \tag{14}$$

If source signal $s(t)$ includes many frequencies, volume velocity is the frequency function of sound source, so:

$$s(t) = \int_{-\infty}^{+\infty} Q(\omega)e^{\mathrm{j}\omega t}d\omega \tag{15}$$

In order to calculate sound transfer function from source point to receiver, source signal should be impulse function at $t = 0$. Based on equation(15), volume velocity is:

$$Q(\omega) = 1 \tag{16}$$

Substituting equation (16) into(11), and calculating equation(11), we can get sound transfer function from source point to receiver.

3. PROCEDURES FOR AURALIZATION IN SMALL ENCLOSURE

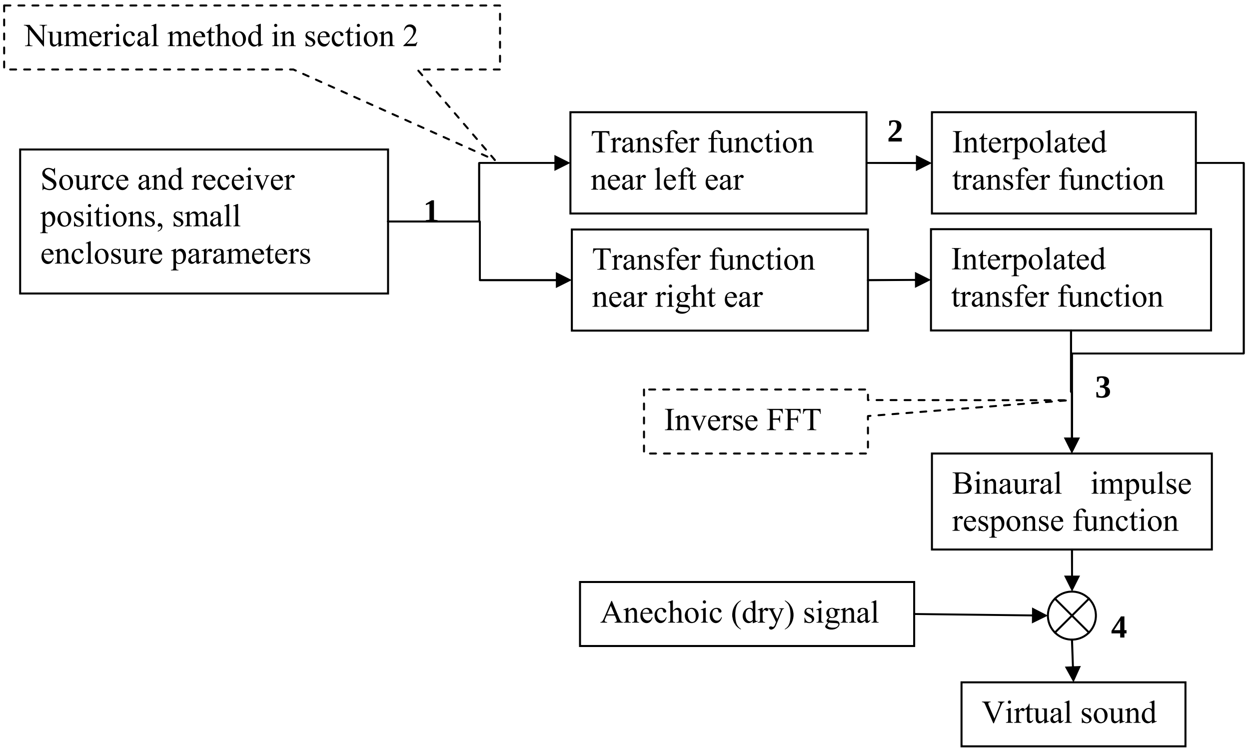

Fig. 1 procedures of auralization software in small enclosures

These procedures are described as:

1. Sound and receiver positions, enclosure parameters are as input parameters. Sound transfer functions at left and right ears' positions are calculated with numerical method in section 2.
2. In order to obtain enough precision, transfer functions are interpolated based on sampling theorem. These two transfer functions are respectively saved as two data files.
3. Two data files are put into MATLAB. With IFFT model, Sound transfer functions are conversed and combined to binaural impulse response function.
4. Virtual sound is generated by convolution binaural impulse response with Anechoic (dry) signal, which is sound signal without any sound field information. Virtual sound is saved as wave file.
5. Audience can hear virtual sound with usual sound software, such as Windows Media Player.

3. EXAMPLE

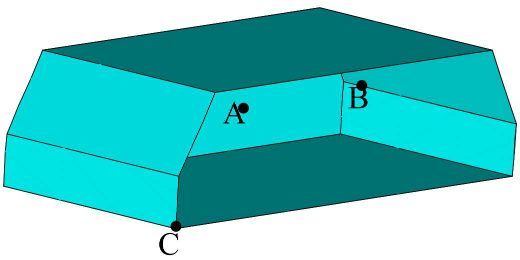

Fig. 2 Car Cab

In this example, auralization is taken into one car cab. Car cab parameters are:

Height, Width and Length are respectively 0.8m, 1.4m. 3.0m. Sound impendence at bottom of car cab is $z_s = 40\rho_0 c_0$. Field points A and B in Fig. 2 are respectively positions of driver head and passenger head. Binaural distance is chosen as 15cm. Field point C is the sound source.

Fig. 3 is one recorded voice signal. The signal length is 1.7s. Sample frequency of the signal is 22.4KHz.

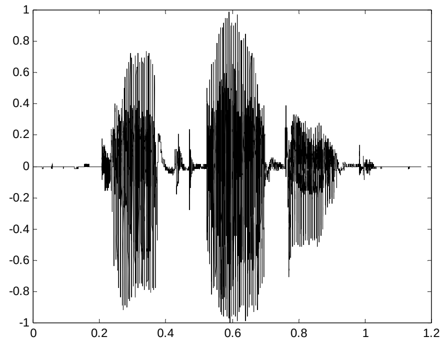

Fig. 3 One Recorded Voice Signal

Taken signal in fig. 3 as dry signal and through procedures in section 3, virtual sound at Field points A and B can be obtained.

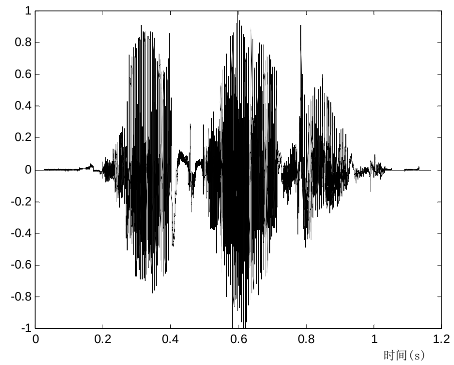

Fig. 4 Virtual Sound at Field Point A

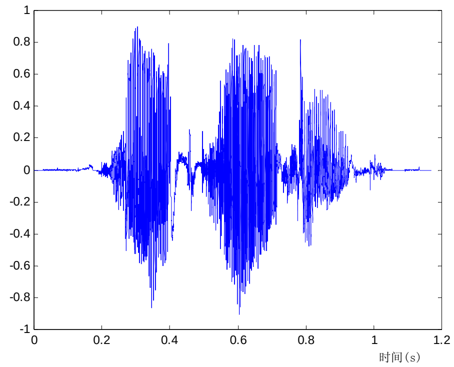

Fig. 5 Virtual Sound at Field Point B

Compared wave shape at fig. 4 with fig. 5, virtual sound at field point A has higher magnitude. Reason of this phenomenon is that driver approach sound source and early sound is the key element for strength of sound.

4. CONCLUSIONS

In this paper, based on FEM model numerical method for sound transfer function and procedures for auralization in small enclosures are presented. Lastly, as an example, the auralization is realized in one car cab model.

ACKNOWLEDGMENT

The author gratefully acknowledges the support of Shaanxi Province natural science foundation (No. 2004E$_2$08) and northwestern polytechnical university outstanding plan (No. 04XD0104).

REFERENCES

[1] K. Kleiner, B.-I. Dalenbäck, P. Svensson, "Auralization—Overview", J. Audio Eng. Soc., 41,816-875 (1993)

[2] W. Ahnert, EARS auralization software. J. Audio Eng. Soc., 41, 894-904 (1993)

[3] B.-I. Dalenbäck, M. Kleiner, P. Svensson, The audibility of changes in geometric shape, source directivity, and absorptive treatment - experiments in auralization, J. Audio Eng. Soc., 41, 905-913(1993);

[4] E. Granier, M. Kleinner, B. Dalerbäck, P. Svensson, "Experimental Auralization of Car Audio Installations", J. Audio Eng. Soc., 44, 835-849 (1996)

[5] Fangli Ning, Juan Wei, "One New Adaptive Finite Element for Calculating Sound Transfer Function in Small Enclosures", *Proceedings of the Tenth International Congress on Sound and Vibration* (ICSV10), 7-10 July 2003, Stockholm, Sweden