VISUALIZATION/AURALIZATION OF SOUND FIELDS FOR ROOM ACOUSTICS*

Hideki Tachibana
Institute of Industrial Science, University of Tokyo
Komaba 4-6-1, Meguro-ku, Tokyo 153-8505, Japan
tachibana@iis.u-tokyo.ac.jp

ABSTRACT: The first step of architectural and acoustical design of a concert-hall/theatre is to choose the fundamental room shape. Secondarily, the shapes of walls and ceiling are designed so as to realize proper reflections and diffused (blended) sound field. As a basic study to investigate these points, 2-dimensional numerical analyses by the finite difference time domain (FDTD) method were performed for typical room shapes, rectangular, fan-shaped, elliptic, etc., with and without diffusive room boundaries. In this presentation, the differences of sound wave propagation and sound diffusivity in the rooms with different shapes and diffusion treatments are visualized by computer animation and the room impulse responses are compared by auralization technique. A new idea to simulate a sound field by combining the FDTD calculation and 4-channel reproduction system is also introduced.

1. INTRODUCTION

The first step of architectural design of concert halls and theatres is to decide the basic room shape. As the basic room shapes, rectangular, horseshoe-shaped, fan-shaped, hexagonal, circular, semi-circular, and elliptic shapes are generally taken. Among them, rectangular shape is often used for classical concert halls represented by Musikvereinssaal in Vienna. Horseshoe-shaped, circular, semi-circular and fan-shaped types are often used for theatres. Elliptic shape is also often used for various kinds of halls. By the differences of such room shapes, the sound propagation characteristics should be much different.

As the second step, the shape of the wall and ceiling is considered. Usually, they are designed irregular to make the sound in the rooms diffused (blended). These room shape design works are very essential in architectural design not only from aesthetic viewpoint but also acoustical viewpoint.

In the author's laboratory, such fundamental studies on acoustical design of halls have been performed using scale modeling and computer simulation techniques. In this paper, some examples of basic investigations made by visual and aural simulation techniques using finite difference time domain (FDTD) method are presented. (In the aural presentation, these results are demonstrated by computer animation and auralization techniques.)

2. NUMERICAL SIMULATION BY FDTD METHOD

Calculation by FDTD Method.

For the purposes of sound field analysis and visualization of room acoustics, such computer simulation techniques as ray-tracing and image-source methods have been developed and being widely used. This kind of techniques based on geometrical acoustics are effective for rough estimation of sound reflection and absorption in a room but it is impossible to exactly deal with such complicated phenomena as sound reflection, diffraction and scattering. To overcome this problem, the "Finite Difference Time Domain (FDTD) method" [1,2] to transient acoustic phenomena has been investigating in the author's laboratory [4-11]. The outline of this calculation method for 2-dimensional space is as follows.

In a 2-dimensional sound field, the sound wave is expressed by the following partial differential equations. Equations (1) and (2) are the momentum equations in x- and y-directions, respectively, and Eq. (3) is the continuity equation.

$$\frac{\partial p(x,y,t)}{\partial x}+\rho\frac{\partial u_x(x,y,t)}{\partial t}=0 \tag{1}$$

$$\frac{\partial p(x,y,t)}{\partial y}+\rho\frac{\partial u_y(x,y,t)}{\partial t}=0 \tag{2}$$

$$\frac{\partial p(x,y,t)}{\partial t}+\kappa\left(\frac{\partial u_x(x,y,t)}{\partial x}+\frac{\partial u_y(x,y,t)}{\partial y}\right)=0 \tag{3}$$

where p is the sound pressure, u_x and u_y are the particle velocities in x- and y-directions, respectively, ρ is the density of the air and κ is the volume elastic modulus of the air.

By expressing these equations in the central finite difference forms by applying a staggered grid system with square-grids ($\Delta_x = \Delta_y$, see Fig.1), the following equations are obtained.

$$u_x^{n+1}(i+1/2\,,j)=u_x^{n}(i+1/2\,,j)-\frac{\Delta t}{\rho\Delta h}\left\{p^{n+1/2}(i+1,j)-p^{n+1/2}(i,j)\right\} \tag{4}$$

$$u_y^{n+1}(i,j+1/2)=u_y^{n}(i,j+1/2)-\frac{\Delta t}{\rho\Delta h}\left\{p^{n+1/2}(i,j+1)-p^{n+1/2}(i,j)\right\} \tag{5}$$

---

*Reprinted from the Proceedings of WESPAC –VIII, Melbourne 2003

$$p^{n+1/2}(i,j)=p^{n-1/2}(i,j)-\kappa\Delta t\left\{\frac{u_x^n(i+1/2,j)-u_x^n(i-1/2,j)}{\Delta h}+\frac{u_y^n(i,j+1/2)-u_y^n(i,j-1/2)}{\Delta h}\right\} \quad (6)$$

where Δh is the size of the square-grid and indices n, $n+1/2$, $n-1/2$ and $n+1$ denote time steps. In the calculations mentioned below, $\Delta h=1$ cm for the spatial grid size and $\Delta t=0.02$ ms for the discrete time step were set.

As the initial condition assuming an impulse source, a smoothly continuous distribution of sound pressure described by the following equation was set (see Fig. 2).

$$p(r)=\begin{cases}1+\cos\pi\dfrac{r}{12\Delta h} & (r<12\Delta h)\\ 0 & (r>12\Delta h)\end{cases} \quad (7)$$

where r is the distance of a grid point from the source position.

Based on the assumption that the boundary is locally reactive, the normal component of the particle velocity on the boundary is expressed as follows.

$$u_n\big|_{boundary}=\frac{p}{Z_n} \quad (8)$$

where $u_n\big|_{boundary}$ is the normal component of the particle velocity on the boundary, is the sound pressure and Z_n is the normal acoustic impedance on the boundary. Here, by assuming that a part of the boundary is approximated by the two sides of a square-grid as shown in Fig.3 and p can be represented by the sound pressure at the center point of the square-grid $p(M,N)$, the following expressions are derived for the x- and y-components of the particle velocity on the boundary.

$$u_x^{n+1}(M+1/2,N)=\frac{p^{n+1/2}(M,N)}{Z_n}n_x \quad (9)$$

$$u_y^{n+1}(M,N+1/2)=\frac{p^{n+1/2}(M,N)}{Z_n}n_y \quad (10)$$

where n_x and n_y are the x- and y-components of the unit vector normal to the boundary under consideration.

To simplify the problem, it was assumed that the normal acoustic impedance on the boundary consists only of real part in this study. In this case, the relationship between the normal acoustic impedance Z_n and the normal sound absorption coefficient α_n is expressed as follows.

$$Z_n=\rho c\frac{1+\sqrt{1-\alpha_n}}{1-\sqrt{1-\alpha_n}} \quad (11)$$

In the calculation mentioned below, it is assumed that $\alpha_n=0.2^{*}$ (corresponding to $Z_n=7357$ Ns/m^3) for over all frequencies to simplify the boundary condition. Under these initial and boundary conditions, the sound pressure and particle velocities at each grid point were calculated successively using Eqs. (4), (5), and (6).

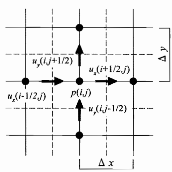


Fig.1 Discretization of the sound field by staggered meshes.

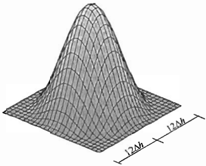


Fig.2 Sound pressure distribution around the source position as the initial condition of calculation

Visualization of Sound Propagation in Rooms.

As the typical room shapes for concert halls and theatres, rectangle (so called "shoe-box style"), fan-shape and ellipse were chosen and the sound propagation characteristics in these 2-dimensional rooms with the same area of 518.4 m^2 were examined by the FDTD method. The left hand sides of Fig.5 show the calculation results in the form of "snap shot" in the time lapse after the emission of the impulse source. (When demonstrating the results by computer animation, the successive propagation of the wave front of the impulse can be clearly visualized.) In each figure, the black circle indicates the source position and the white one indicates the receiving position for the calculation of impulse response mentioned later.

Comparison of these figures reveals that the propagation of the wave front is much different in each room shape. In the rectangular room, it is clearly seen that the number of wave front increases with the progress of time, whereas in the fan-shaped and elliptic rooms, a tendency that the wave front deflects and concentrates is seen. Especially, in the elliptic room, it is clearly seen the wave front focuses at around the source position and its symmetrical point alternately.

The impulse responses at the receiving point in each room are shown in Fig.6 (a). In these results, it is seen that the

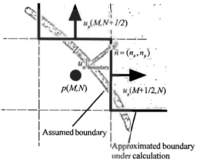


Fig.3 Discretization of the sound field near the room boundary

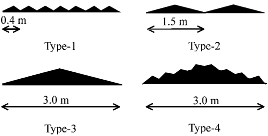


Fig.4 Shapes of diffusers under investigation

reflections are dense and smoothly diminishing in the rectangular room, whereas they are scattered and uneven in the fan-shaped and the elliptic rooms.

Basic Study on the Effect of Sound scattering by diffusers.

In concert halls and theatres, wall and ceiling are generally made irregular to increase sound diffusivity. To examine the effect of such diffusion treatments, the FDTD calculation was again performed for the three types of rooms by making their walls irregular. As the shape of irregular wall, a zigzag shape (Type-2 in Fig.4) was assumed. The snap shots of the calculation results are shown in the right hand sides of Fig. 5. By comparing the results with those in the case of no diffusion treatment shown in the left hand sides of Fig. 5, it is clearly seen that the distinct wave fronts have been much diminished and scattered in all of the three rooms.

The impulse responses at the receiving points in the three rooms were calculated in this case, too. The results are shown in Fig. 6(b) in comparison with those without diffusion treatment shown in Fig. 6(a). In these results, it is obviously seen that the impulse responses have become much denser and smoother than the case of without diffusion treatment. When hearing these impulse responses through a loudspeakers or headphones, it can be clearly judged that the reverberation decays have much improved to be natural and smooth by the diffusion treatment, although the early fluttering sounds caused by the sound concentration are still slightly remaining in the cases of the fan-shaped and elliptic rooms. This fact indicates that the general tendency of sound concentration caused by the fundamental room shape can not be prevented completely by this kind of diffusion treatment on the room boundaries.

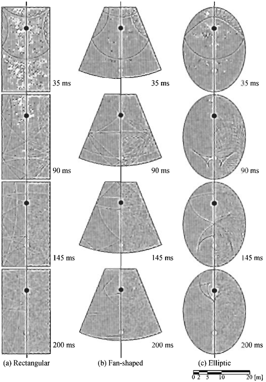
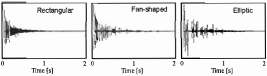


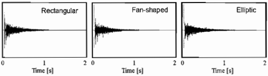
Fig. 5 Sound propagation in a rectangular (a), fan-shaped (b) and elliptic (c) rooms without diffusing treatment (left hand side) and with that (right hand side)

In order to examine the effect of sound scattering by diffusers in more detail, a further study was performed on the rectangular room. In this study, four kinds of zigzag shapes shown in Fig. 4 were assumed. Among them, Type-1, Type-2 and Type-3 are similar in shape but the size was varied in three steps. The ratio of the height of the apex to the width of a triangle was set 0.15. Type-4 is a "two-way" diffuser composed of Type-3 and Type-1.

Figure 7 shows the calculation results. To compare these results with those in the case of no diffusion treatment shown in the left hand sides of Fig. 5, it is clearly seen that the sound is scattered after the first reflection on the diffusive boundaries and the space is filled with sound pressure fluctuation. In the results for Type-1, Type-2 and Type-3, it is seen that the scattering effect is dependent on the size of the diffusers. That is, in the case of Type-1, relatively strong and continuous wave fronts are still remaining, whereas they are much diminished in the case of Type-3. In the result for Type-4, the effectiveness of "two-way" diffuser can be observed.



(a) Without diffusing treatment



(b) With diffusing treatment

Fig.6 Calculation results of impulse responses at the receiving points shown in Fig.5.

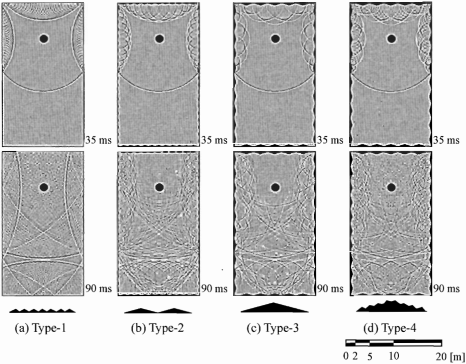
In the calculation by the FDTD method, instantaneous sound pressure at every mesh point is obtained. By squaring the sound pressure, instantaneous potential energy distribution in the room can be obtained and consequently the time variation of acoustic diffusivity in the room can be evaluated quantitatively from a viewpoint of the spatial uniformity of sound energy [11].

The Effect of Sound Diffusing Treatment in an Elliptic Hall.

In the acoustic design of the Small Hall in the Kiryu City Hall, in Japan, we had a chance to apply the numerical simulation technique using the FDTD method [5]. At the first stage of the design of this hall, the architect proposed elliptic room shape. This shape is very dangerous and we proposed to make the walls zigzag-shaped with forward-bent surfaces in order to prevent acoustic defects caused by the basic room shape. To examine the effect of such diffusion treatment (and to make the architect be convinced), numerical simulation was performed.

In the calculation, spatial grid size of 5 cm and discrete time step of 0.08 ms were set and the sound absorption coefficients of the wall, forward-bent surfaces and floor were assumed 0.13, 0.50 and 0.12, respectively. The surface of the ceiling was treated as perfectly absorptive because high absorptive finishing was designed on the ceiling.

Figure 8 shows the calculation results for the two conditions, with and without diffusing treatment, in the form of "snap shot" in the time lapse after the emission of the impulse source. In the case of without diffusing treatment, successive sound focusing is clearly seen, whereas sound is much scattered and blended in the case of with diffusing treatment by the effect of the zigzag walls.



(a) Type-1 (b) Type-2 (c) Type-3 (d) Type-4

Fig.7 Comparison of sound propagation in the rectangular room with four types of diffusing treatments.

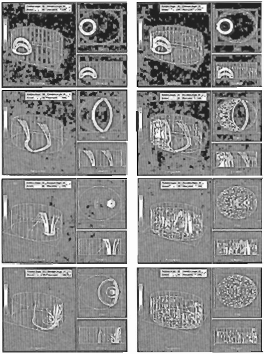

(a) without diffusing treatment (b) with diffusing treatment

Fig.8 Comparison of sound propagation in a 3-dimensional elliptic hall with and without diffusing treatment.

After the construction of this hall, room impulse responses were measured and they were compared with those calculated by the FDTD method. Two examples of the comparison are shown in Fig. 9 and we can see a fairly good agreement between the calculation (upper figures) and the real measurement (lower figures).

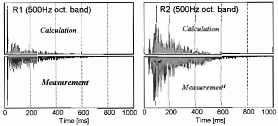


Fig.9 Comparison of impulse response between calculation and measurement.

3. TWO-DIMENSIONAL AURALIZATION OF ROOM IMPULSE RESPONSE

As a further application of the numerical simulation by the FDTD method, we are now developing a technique to auralize the calculated impulse responses with spatial information [8,10]. Figure 10 shows the principle of the "4-channel numerical sound field simulation system". In this system, the uni-directional impulse responses for four orthogonal directions are firstly calculated by the FDTD method as follows.

$$p^{n+1/2}_{directional}(i,j) = p^{n+1/2}(i,j)\cdot f(\theta) \tag{12}$$

$$f(\theta) = \frac{1+\cos\theta}{2} \tag{13}$$

where θ is the sound incident angle to the receiving point. The incident angle is calculated using the sound intensity components in x- and y-directions at the receiving point. In the staggered grid system, the sound intensity at the grid point (i, j) is calculated as follows and the incident angle θ can be calculated by Eq. 16.

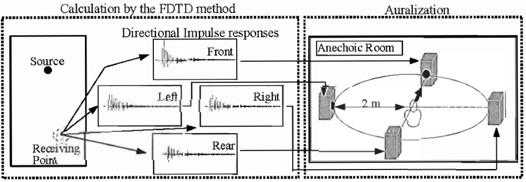


Fig.10 Outline of the 4-ch. numerical sound field simulation system

$$I_x^{n+1/2}(i,j) = p^{n+1/2}(i,j)\cdot\frac{u_x^n(i+1/2,j)+u_x^n(i-1/2,j)}{2} \qquad (14)$$

$$I_y^{n+1/2}(i,j) = p^{n+1/2}(i,j)\cdot\frac{u_y^n(i,j+1/2)+u_y^n(i,j-1/2)}{2} \qquad (15)$$

$$\theta = \tan^{-1}\left(\frac{I_y^{n+1/2}(i,j)}{I_x^{n+1/2}(i,j)}\right) \qquad (16)$$

Next, the four directional impulse responses are reproduced from four loudspeakers set in an anechoic room as shown in Fig.9. At the center point or the simulated sound field, we can hear the impulse response with spatial impression. (At present, the system is for 2-dimension but it is easily expanded to 3-dimentional, in principle.) By applying this auralization system, we are now making subjective hearing tests on the effect of sound diffusing treatments on the walls of concert halls [10]. Of course, by convolving an arbitrary dry source with the 4-channel impulse responses, we can hear the sound with 2-dimensional spaciousness, in principle. At present, however, it is difficult to calculate the impulse response up to high frequencies enough for listening music.

4. CONCLUSIONS

As a basic study on visualization of room acoustics using numerical simulation technique, the sound propagation in rooms of different shapes and the scattering effect of acoustic diffusers have been investigated by applying the FDTD method. As a result, it has been found that this kind of sound field simulation technique is very effective to get intuitive comprehension of acoustic phenomena in rooms. It will be a useful tool for acoustic education not only for students and acoustic engineers but also for architects who design concert halls and theatres.

REFERENCES

[1] J.G. Meloney and K.E. Cummings, "Adaptation of FDTD techniques to acoustic modeling", *11th Annu. Rev. Prog. Applied Computational Electromagnetics*, Vol.**2**, 724 (1995)

[2] J. Lovetri, D. Mardare and G. Soulodre, "Modeling of the seat dip effect using the finite-diffirence time-domain method", *J. Acoust. Soc. Am.*, **100**, 2204 (1996)

[3] S. Sakamoto, Y. Tokita and H. Tachibana, "Calculation of impulse responses of rooms by using of the finite difference method", *Proc. of ASA and ASJ Third Joint Meeting*, p.1307 (1996)

[4] S. Sakamoto and H. Tachibana, "Calculation of impulse responses in 3-D sound field with absorptive boundary by the finite difference method", *Proc. of Inter-Noise 97*, p.1597 (1997)

[5] S. Sakamoto, F. Okabe and H. Tachibana, "Calculation of impulse responses in a hall by the Finite Difference Method, *Proc. Spring Meet. Acoust. Soc. Jpn.*, p.785 (1999) (In Japanese)

[6] T. Yokota, T. Seimiya, S. Sakamoto and H. Tachibana, "Difference in acoustic effect of sound diffusers due to room shapes", *J. Acoust. Soc. Jpn.* (E), **21**, No. 5, p.283 (2000)

[7] Y. Naito, S. Sakamoto and H. Tachibana, "Study on perfectly absorptive boundary layer for open region numerical analysis by F.D.M. – Method considering a travelling direction of sound wave –", *Proc. Spring Meet. Acoust. Soc. Jpn.*, p.849 (2001) (In Japanese)

[8] S. Sakamoto, T. Seimiya, T. Yokota and H. Tachibana, "Multi-dimensional sound field reproduction based on numerical simulation –a trial of 4 channel system for 2-dimensional sound field-", *Proc. Autumn Meeting of Acoust. Soc. Jpn.*, Vol. 2, p.799 (2001) (in Japanese).

[9] T. Yokota, S. Sakamoto and H. Tachibana, "Visualization of sound propagation and scattering in rooms", *Acoustical Science & Technology* **23**, 1, p.40 (2002)

[10] S. Sakamoto, T. Yokota and H. Tachibana, "Multi-dimensional sound field reproduction based on the finite difference time domain method", *Proc. Forum Acousticum* Sevilla 2002

[11] T. Yokota, M. Iiduka, S. Sakamoto and H. Tachibana, "Differences of sound pressure level distribution due to the variation of room shape", *Proc. 8th WESPAC* (2003)