Simulation of Room Impulse Response by using Hybrid Method of Wave and Geometrical Acoustics

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More and more attention has been paid to the auralization during the past few years. In this paper, the auralization technique was reviewed at first. Then, to realize the hybrid broad-spectrum simulation in the auditorium including the low frequency, an improved hybrid algorithm, which combines geometric acoustics and the wave acoustics method, has been proposed. The middle and the high frequency of the impulse response were simulated by using Odeon software, while the low frequency of the impulse response was simulated through the FDTD method. The method can deal with truly lower frequency bands simultaneously by using the low frequency. Furthermore, the phase of the impulse was reconstructed through the Hilbert transform. The results validated the applicability of the improved method and they have also shown that FDTD can improve auralization, although it not always create more virtual sound field.

Key words: Subjective preference, Auralizationg;impulse response;convolution;subjective experiment;phase reconstruction;FDTD

1. INTRODUCTION

More and more attention has been paid to the auralization during the past few years. The foundation of the auralization is Computer simulation of the room acoustics. Computer modeling of room acoustics was proposed during the 1960s by Schroeder et al. [1] and was used in practice by Krokstad et al. [2] and Schroeder [3]. The computer modeling of room acoustics has been traditionally limited to the ray tracing method and image source method. These are high-frequency techniques based on geometrical acoustic theory, and they developed rapidly in the past 40 years. However, many wave phenomenons are neglected in these simulations. Till now, it is well known that such a situation is not valid in low frequency. During the recent decade, low frequency simulation has been investigated by many authors and its importance and application in the modeling have been pointed out [4–8]. The investigations carried out by Kuttruff [9], Hodgson[5], Dalenback et al. [6] and Lam [7] have shown that the low frequency impulse response not only affect the accuracy of the calculation of acoustical parameters such as sound pressure levels and reverberation time, but also have influence on the quality of auralization. The ray-tracing and the sound image method is only appropriate in the middle-frequency range. Direct time-domain approaches seem can be used to solve the low frequency of the impulse response more appropriately.

In this paper, in order to investigate the low frequency phenomenon, the true wave nature of sound must be considered. FDTD method is used for solving the low-frequency range problem. FDTD method means solving approximately within the finite difference time-domain. FDTD simulation is not popular for solving problems in linear acoustics. In contrast, it is one of the very few techniques used to solve nonlinear wave equations that govern computational fluid mechanics. [10]FDTD is a digital computation technique based on wave equation. This method meets most of the demands required for a good brute force numerical solution of the problem: All calculations are done directly in time domain, acoustical equations are locally resulting in an explicit formulation, and the numerical formulation is itself conservative. A direct calculation in time domain has the advantage of speed, but poses some problems for describing frequency-dependent material characteristics, such as boundary conditions. Until now there is not a well developed FDTD for the room acoustics.

This paper is organized as follows. First the simulation basics are reviewed, especially within the low frequency range. Then the geometric acoustics method was used to calculate the impulse response at the middle-frequency. Further more; FDTD was used to calculate the impulse response at the low-frequency. Finally, the two different methods were synthesized to improve the accuracy of the FDTD simulation within low-frequency. It will be shown how the simulation method can be used as an amendment to ray tracing for low frequencies

2. Full Band Impulse response simulation

2.1 Middle-frequency simulation

There is a number of different modeling techniques currently used to predict the acoustics of the auditoria. Many prediction methods based on geometrical acoustics allow for some inclusion of the effects of diffuse reflection. The most popular one include ray tracing, the image method, and various forms of beam tracing. Ray tracing [11] creates a dense spread of rays, which are subsequently reflected around a room and tested for intersection with a spherical detector. The energy attenuation of the rays and distances traveled are used to construct the echogram. Although relatively simple to implement, the algorithm has inherent systematic errors whereby spurious reflections can be created due to using a non point detector whilst other valid reflections are missed as the rays diverge [12]. Hence image method can provide a statistical evaluation of a sound's likely incidence at a spherical representation of the receiver; the image method can provide the exact information at a point receiver.

This method is of questionable utility for detailed echogram prediction and for auralization even a substantially higher number of rays are used. The reason for this is that the geometrical acoustic can not accurately solve the lower frequency impulse response. In reality, spatial and temporal of low frequency can only be solved in different ways.

In this paper, we have used the software to simulate the middle frequency of the impulse response. The FDTD method was only used as supplementary simulation of the low frequency. There three principal parameters which have to be chosen when carrying out a calculation in ODEON4.0, and which can have a significant effect on the results. "Although a lot more experience is needed before definitive rules can be laid down, it is possible to give some indication of how these should be set for best results."

Figure 1 shows the calculation model. In the figure,100000 rays are followed up to the sixth reflection order. The transition order in the ODEON software is set to 6, so after order 6 the rays' reflection directions are chosen at random distribution following the Lambert's law. The impulse response sampling is set at 0.1ms.

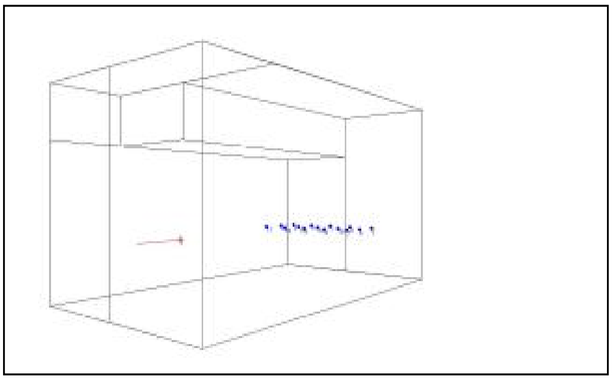

Figure 1. The model of simulation in ODEON. (The red is the source,the blue is the receiver)

The reflect-gram displays the arrival of early reflections to a receiver. When the early reflections are calculated from detected image sources, it follows that each single reflection can be separated independently. The single reflection in this paper was set to 6 according to the transition order. In addition to arrival time and energy of the reflection, it is also possible to get information about the direction and which surfaces are involved in the reflection path.

Figure 2 shows the simulation result of the impulse response on the geometrical acoustics. From the fig.2, the middle of the impulse response of the listen room can be simulated. The amplitude of the impulse response has been normalized. The impulse responses show the early reflection in detail. The frequency responses can be calculated through the FFT transform. Figure 3 shows the frequency response of the full band of a listen room.

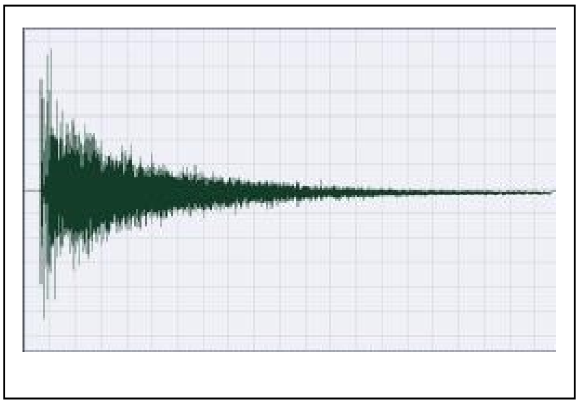

Figure 2. The impulse response of the simulation in middle frequency.

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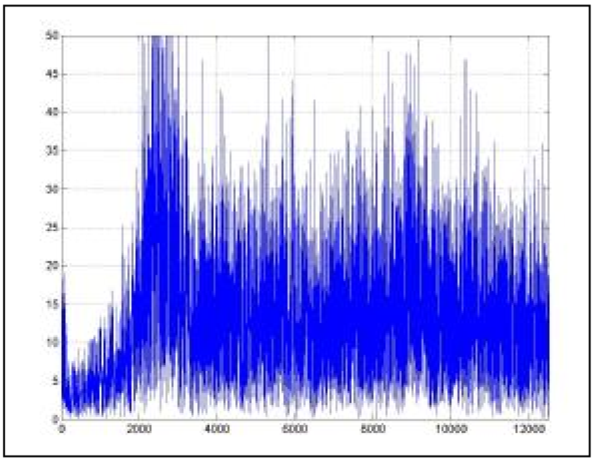

Figure 3. The frequency response of the simulation in Odeon.

3. FDTD Simulation of Room's Low-Frequency Impulse

3.1 The FDTD simulation Theory

The Cartesian staggered grids are used in the simulation here, i.e., in every grid position the acoustical pressure is half step away from its nearest particle velocity components. We should know that the time steps between pressure and particle velocity components in each grid position are also staggered, as we can see in the equations below. For the sake of simplicity, we suppose that the spatial discrete steps of three different directions are the same in distance $\delta x = \delta y = \delta z = \delta h$, hence the FDTD approximations to the equations of linear acoustics in air become [13]

$$u_x^{[l+0.5]}(i+0.5,j,k) = u_x^{[l-0.5]}(i+0.5,j,k) - \frac{\delta t}{\rho_0 \delta h} \times \left[p^{[l]}(i+1,j,k) - p^{[l]}(i,j,k) \right] \quad (1)$$

$$u_y^{[l+0.5]}(i,j+0.5,k) = u_y^{[l-0.5]}(i,j+0.5,k) - \frac{\delta t}{\rho_0 \delta h} \times \left[p^{[l]}(i,j+1,k) - p^{[l]}(i,j,k) \right] \quad (2)$$

$$u_z^{[l+0.5]}(i,j,k+0.5) = u_z^{[l-0.5]}(i,j,k+0.5) - \frac{\delta t}{\rho_0 \delta h} \times \left[p^{[l]}(i,j,k+1) - p^{[l]}(i,j,k) \right] \quad (3)$$

$$p^{[l+1]}(i,j,k) = p^{[l]}(i,j,k) - \frac{\rho_0 c^2 \delta t}{\delta h} \Big\{ \left[u_x^{[l+0.5]}(i+0.5,j,k) - u_x^{[l+0.5]}(i-0.5,j,k) \right] + \left[u_y^{[l+0.5]}(i,j+0.5,k) - u_y^{[l+0.5]}(i,j-0.5,k) \right] + \left[u_z^{[l+0.5]}(i,j,k+0.5) - u_z^{[l+0.5]}(i,j,k-0.5) \right] \Big\} \quad (4)$$

where i, j, k are integers and stand for the spatial positions. The upper index l is also integer and stands for the discrete time. For the simulation here, we suppose the local air density ρ_0 equals $1.21 kg/m^3$ and the local sound speed equals $344 m/s$.

3.2 The FDTD Boundary Conditions

Locally reacting surface (LRS) is supposed on the boundary, where the normal component of the particle velocity at the surface of the wall depends on the sound pressure in front of the wall element and not on pressure in front of neighboring element. On the absorbing boundary conditions, there is a relationship between the normal component of particle velocity on the boundary (u_n) and its nearest sound pressure (p)

$$u_n \Big|_{boundary} = \frac{p}{Z_n} \quad (5)$$

where Z_n is the normal acoustic impedance on the boundary, and[14]

$$Z_n = \rho_0 c \left(1 + \sqrt{1-\alpha} \right) / \left(1 - \sqrt{1-\alpha} \right) \quad (6)$$

where α is the normal sound absorption coefficient on the boundary.

3.3 The Stimulus of The FDTD

For the room impulse response (RIR) can reveal most of the acoustic characteristics of a room, an impulse source is given as an initial condition. The frequently used source is Gaussian impulse source, which can be expressed as

$$p(t) = -A(t-t_0)\exp\left(-\left(t-t_0\right)^2 / T_0 \right) \quad (7)$$

Where t_0 is the time when the impulse wave node exists, and the magnitude of A determines the impulse's amplitude. The Gaussian width T_0 is used to determine the frequency range excited by the Gaussian impulse, and the width of T_0 is determined by the spatial discrete step δh, and the spatial steps are limited by computer's capability and constrained by a stability condition: $\delta t \le \delta h / (\sqrt{3} c)$. Generally the spatial δh step is chosen among the range of 1/10 to 1/20 of the relevant wavelength.

3.4 Model of the Listen Room in the FDTD

Considering the irregularity of wall and the interested frequency range, the FDTD mesh cell size is $\Delta x = \Delta y = \Delta z = 3cm$, and the time step is determined by the 3D stability condition: $\Delta t = \Delta h / (\sqrt{3} c)$,where Δh is spatial step and c is sound speed. FDTD simulation capability depends on fineness of mesh grids. For the mesh grids mentioned above, such model can simulated sound propagation of frequency up to 1kHz, considering spatial step of mesh should be less than one tenth of the smallest wavelength. First a model of listen rooms is established. The listen room has the volume of 7.62m by4.25m by 3.95m.

The source model of equation (7) is set at the position of S (2.2, 6.6, 1.2), that is 2.2m by length,6.6m by width and 1.2m by height. In order to investigate different positions' acoustics, we also place some receivers in the listen room, and they are P1(2.2, 1.0, 1.2), P2(2.2, 1.6, 1.2), P3(2.2, 2.2, 1.2), P4(1.6, 1.0, 1.2), P5(1.0, 1.0, 1.2).

4. The Impules Response Synthesis Through The Hilbert Transform

The impulse response can be transformed from the time domain into the frequency domain. The impulse responses with different frequency scope have been calculated in different way. In this paper, different frequency response scope has been synthesized. Some facts about the Hilbert transform are stated here without proof [15]. Further the Hilbert transform is linear. Consequently, for any function for which a Fourier transform exists. The impulse response with the minimum phase can be reconstructed from the synthesized frequency response. We can

Figure 2 shows a middle frequency impulse response x (t), and its FFT transform, X (t) which was simulated through the traditional method. Figure 4 shows a low frequency impulse response x (t), and its FFT transform, X (t),which was simulated through FDTD method. We used the lower frequency response that simulated through the FDTD method as the full band. The lower cut of the synthesized frequency is set at the 315 Hz, because the FDTD method simulation's limitation. The middle frequency response was used the traditional method. The lower frequency energy of the traditional method was filtered out. Figure 5 shows the synthesis result of the full band frequency impulse response.

The amplitude of the frequency has been constructed after the synthesis. The amplitude space and the phase space makes up the Hilbert space. The minimum phase space can be reconstructed through the Hilbert transform. The Hilbert transform was computed by using the same amplitude From the fig 5,we can see the amplitude of the synthesized frequency.

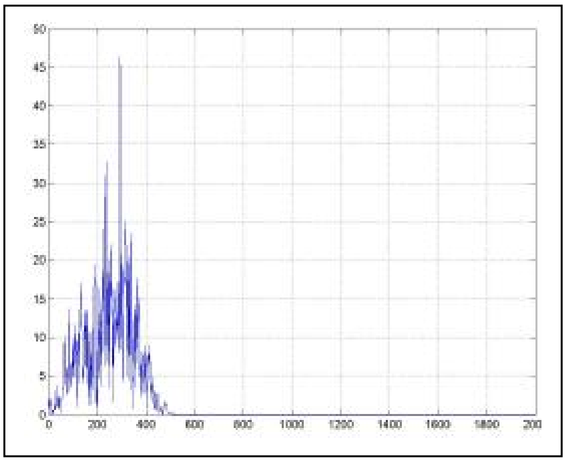

Figure 4. The simulated frequency response used FDTD method

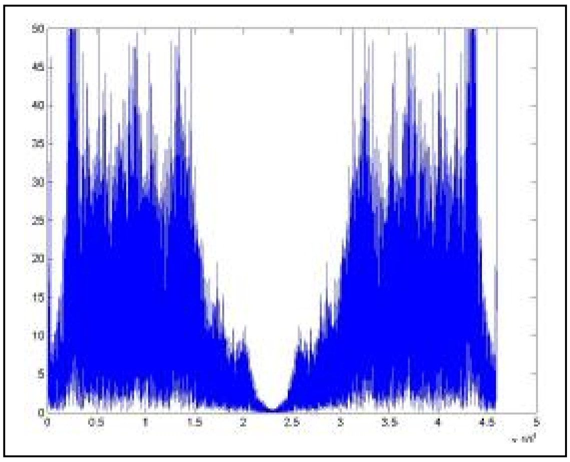

Figure 5. The systhesised frequency response with full band.

5. CONCLUSIONS

The subject of this paper is simulation method in the low frequency. The FDTD method was used to simulate the impulse response in the low frequency. The Hilbert transform has been used in the phase reconstruction. A real listen room's response has been use to test the reconstruction's fidelity. The subjective evaluation has been carried to verify the syntheses.

In our investigation above, we find that the low frequency impulse response simulated by the FDTD has great space information than that simulated by the traditional method. The two low frequency impulse response from different method have distinctly difference. The further study on the phase reconstruction should be done to testify the low frequency impulse response simulation. And more research work on experiments on the accuracy and efficiency for the simulation of full frequency bands will be done in the future.

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