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TIME DOMAIN LARGE-SCALE FINITE ELEMENT SOUND FIELD ANALYSIS OF A MULTI-PURPOSE HALL

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Abstract

The authors have been developing Large-scale Finite Element Sound Field Analysis, or LsFE-SFA for short, to analyze sound fields in architectural rooms with complicated boundary conditions. The main purpose of this paper is to show its applicability and accuracy when a realistic large-scale sound field is to be analyzed in the time domain. A multi-purpose hall(A-hall, for short) with the volume of more than 37,000 m^3 and about 2,500 seats is analyzed hereafter. At first, both mathematical basis of time domain LsFE-SFA is explained briefly. Then, both frequency and time domain LsFE-SFA were applied onto the sound field in A-hall. In the analyses, two types of boundary modeling, with or without balcony, were given into the computations. The values of absorption coefficient of materials except auditorium side-walls were given by referring literatures, and that of side-walls were given by in-situ measurement following some of the authors' EA-Noise method. By the frequency domain LsFE-SFA, sound pressure level distribution contour maps at 63 and 125 Hz were computed and the results were confirmed to be good. Then, the 1/3 octave band filtered impulse responses centered at 63 Hz and 125 Hz were computed by the time domain LsFE-SFA, and fair agreements with measured data were found. Finally, the results by the time domain LsFE-SFA were transformed into the frequency domain and the relative sound pressure level distributions of them showed excellent agreement with those computed by the frequency domain LsFE-SFA directly.

1. INTRODUCTION

In the designing process of architectural and/or environmental acoustics including building acoustics, various simulation systems based on the geometrical acoustics have been practically utilized quite a lot. It is indispensable, however, to take proper account of the wave nature of the sound field into the system especially when closer investigations are required. On the other hand, numerical methods based on the wave equation are logically advantageous in dealing with the nature, and various methods have also been developed to solve problems of many kinds. Comparing with the BEM, that can reduce a system's dimensions by one, the FEM is usually said to be unsuited to be applied onto problems of architectural acoustics because they usually consist both of complicated three dimensional structures and of large amount of air volume. Simple mathematical structure of FEM, however, makes its matrix computation simple and efficient enough especially when it is computed on a vector and/or parallel processor(s).

The authors have been developing a system of large-scale finite element sound field analysis, or LsFE-SFA, and also have presented papers both in time and frequency domains [1], [2], [3]. In the computations of the kind, some reliable impedance data of boundaries are required to assure their accuracy. Then, the authors have also proposed a experimental method to obtain a surface's impedance in-situ [4], and some trial measurements and computations were conducted [5].

In this paper, a multi-purpose hall(A-hall) with the volume of about 37,000 m^3 and with about 2,500 seats is analyzed to show the applicability and accuracy of time domain LsFE-SFA when a realistic large-scale sound field is to be analyzed.

2. THEORETICAL DESCRIPTION

Following a standard finite element procedure based on the principle of minimum total potential energy applied onto the three-dimensional sound field, the following discretized matrix equation in the frequency domain can be obtained:

$$[K]\{p\} + i\omega[C]\{p\} - \omega^2[M]\{p\} = i\omega\rho v_0\{W\} \tag{1}$$

Where, $[M]$, $[C]$ and $[K]$ denote acoustic mass, dissipation and stiffness matrices respectively; and $\{p\}$, ρ, ω, u and $\{W\}$ are sound pressure vector, air density, angular frequency, displacement and distribution vector respectively. Assuming that $\cdot$ and $\cdot\cdot$ to be first and second order derivative with respect to time respectively, the equation in the time domain can be:

$$[M]\{\ddot{p}\} + [C]\{\dot{p}\} + [K]\{p\} = \rho\omega^2 u\{W\}(= \{f\}). \tag{2}$$

With a shape function, $\{N\}$, the acoustic element matrices that construct global matrices in the Eq.(1) are given by

$$[K]_e = \int_e \left(\{\frac{\partial N}{\partial x}\}\{\frac{\partial N}{\partial x}\}^T + \{\frac{\partial N}{\partial y}\}\{\frac{\partial N}{\partial y}\}^T + \{\frac{\partial N}{\partial z}\}\{\frac{\partial N}{\partial z}\}^T \right) dV, \tag{3}$$

$$[M]_e = \frac{1}{c^2}\int_e \{N\}\{N\}^T dV, \tag{4}$$

$$[C]_e = \frac{1}{c}\int_{e'} \frac{1}{z_n}\{N\}\{N\}^T dS. \tag{5}$$

where c and z_n are sound speed and normal surface impedance respectively, and e' denotes the surface area to be integrated.

In the time domain, we employed Newmarkβ method to solve the eq. (2) step by step. If $\{p\}_t$, $\{\dot{p}\}_t$ and $\{\ddot{p}\}_t$ at t, are known, then, $\{p\}_{t+\Delta t}$ and $\{\dot{p}\}_{t+\Delta t}$ can be given by

$$\{p\}_{t+\Delta t} = \left\{ \{p\}_t + \Delta t\{\dot{p}\}_t + (\Delta t)^2(\frac{1}{2} - \beta)\{\ddot{p}\}_t + (\Delta t)^2\beta\{\ddot{p}\}_{t+\Delta t} \right\}, \quad (6)$$

$$\{\dot{p}\}_{t+\Delta t} = \left\{ \{\dot{p}\}_t + \Delta t(1 - \gamma)\{\ddot{p}\}_t + \Delta t\gamma\{\ddot{p}\}_{t+\Delta t} \right\}. \quad (7)$$

where Δt is time interval between t and $t + \Delta t$, and $\gamma,\ \beta$ are parameters(in the following sections, $\gamma = 1/2$ and $\beta = 1/4$ are assumed). Then, with the Eqs. (6) and (7), we can transform Eq. (2) into:

$$\left[[M] + \frac{\Delta t}{2}[C] + \beta(\Delta t)^2[K] \right] \{\ddot{p}\}_{t+\Delta t} = \left\{ \{f\}_{t+\Delta t} - [C]\{P\} - [K]\{Q\} \right\} \quad (8)$$

here,

$$\{P\} = \left\{ \{\dot{p}\}_t + \frac{\Delta t}{2}\{\ddot{p}\}_t \right\}, \quad \{Q\} = \left\{ \{p\}_t + \Delta t\{\dot{p}\}_t + (\frac{1}{2} - \beta)(\Delta t)^2\{\ddot{p}\}_t \right\}. \quad (9)$$

Thus, $\{\ddot{p}\}_{t+\Delta t}$ can be obtained by solving eq.(10) that is in the form of a linear equation:

$$[A]\{x\} = \{b\}. \quad (10)$$

3. COMPUTATIONAL SETTINGS

3.1. Boundary Conditions

3.1.1. Shape Modeling

At the first stage of the study, simplified modeling illustrated in Fig. 1 was given into LsFE-SFA; and we assumed two types of modeling, Type-1 and Type-2, to compare the effect of balcony onto the sound field. Based on preceding investigations using Cone Beam Method(Raynoise), shapes of all the seats were neglected in both types.

3.1.2. Absorption Modeling

Simplified absorption settings were also assumed for both Types-1 and -2. All the absorption coefficients, α, except for that of auditorium side-walls were given by referring literature data. The absorption of side-walls were given as follows.

The auditorium side-walls are wooden ribbed structures backed by absorptive materials(see Fig. 2). With EA-Noise method[4], absorption characteristics of a material can be measured point by point *in-situ*. Then, with the EA-Noise method utilizing a mobile sound source, surface impedances at points-a and -b were measured, and the averaged absorption coefficients were obtained from the measured impedance values. At this stage, to use the simplified shape modeling mentioned above, a simple absorption condition like this is preferable. In addition, the absorption characteristics of a seat was also measured by the method and they are included into that of floor.

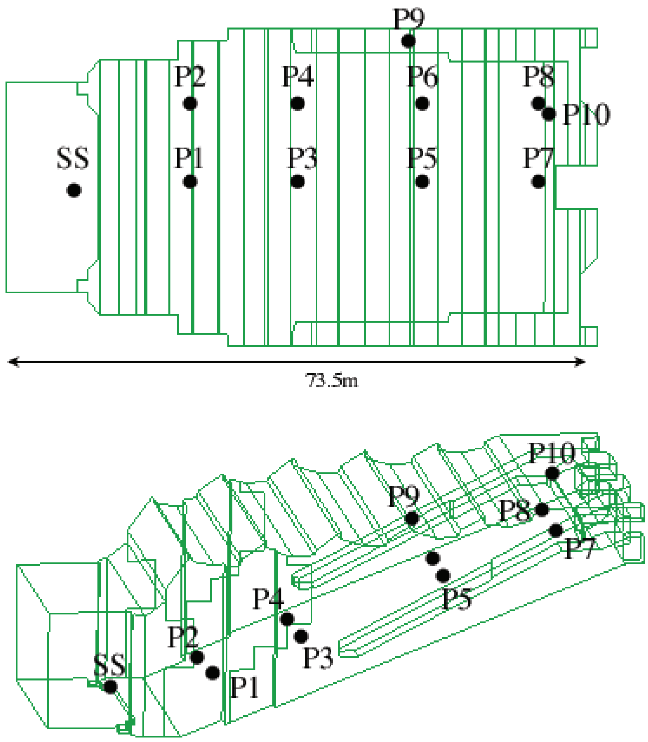

Figure 1. Boundary modeling(Type-1: without Balcony, Type-2: with balcony); SS: loudspeaker location; P1$\sim$10: receiving points.

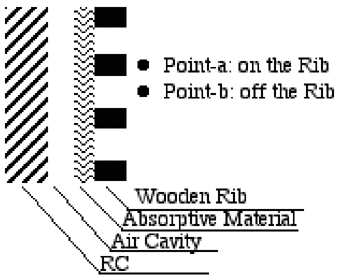

Figure 2. Section view of an auditorium side-wall with wooden ribs.

Then, all the impedance values given to the FE-computation were calculated with the absorption coefficient values assuming that the imaginary parts of the impedances to be zero.

3.2. Finite Element Method Settings

In the following investigations, target frequencies are set to 63 and 125 Hz. In the FE-analysis, 27-node spline acoustic element[6] were utilized and FE-mesh was set to satisfy spacial division requirement at 125 Hz, or $\lambda/d > 4.8$, which resulted *D.O.F* to be 2,630,435. Tow kinds of analyses, that are in the frequency and time domains, were conducted, and memory sizes of them are 8.1 GB and 4.9 GB respectively.

In the frequency domain, a point source which radiates steady state pure tone at 63 or 125 Hz was assumed on the stage at "SS" in Fig.1. To solve the linear equation in Eq.(1), an iterative

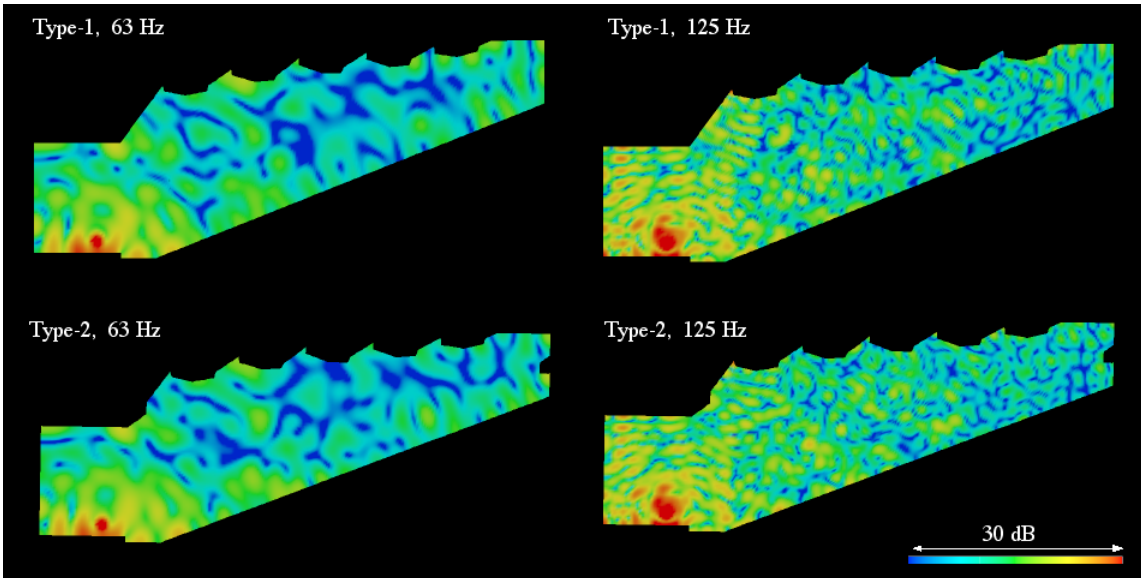

Figure 3. Sound pressure level distribution contour map obtained by LsFE-SFA in the frequency domain. Section view including SS-P1-P3-P5-P7.

method, that is Conjugate Orthogonal Conjugate Gradient method(COCG method, for short), was employed.

In the time domain, a point source which radiates 1/3 octave band noise centered at 63 or 125 Hz was assumed. To model the sound source numerically, filtered OATSP signal[7] through 1/3 octave band pass filter was used. Here, Newmarkβ method was employed to compute the sound pressure response step by step with time-step $\Delta t = 0.05$ ms, and COCG method was also employed to solve the linear equation, Eq.(10), at each step.

4. RESULTS AND DISCUSSION

Relative sound pressure level distributions at 63 and 125 Hz obtained by LsFE-SFA in the frequency domain are illustrated in Fig.3. Though it is not easy to find distinct difference between the results of the two types of modeling there, smaller wave patterns can be seen in the SPL distribution contour map of 125 Hz than those of 63 Hz. Proper sound propagation patterns outgoing from the sound source can also be observed regardless of modeling types or frequencies.

Then, in Fig.4, filtered impulse responses within 1/3 octave band centered at 125 Hz obtained by LsFE-SFA in the time domain are compared with those by measurements. The measurements were conducted in the realistic A-hall; and an omnidirectional dodecahedron speaker was placed at the same location as of SS in the computation radiating the Maximum-Length-Sequential signal to measure impulse responses at the points No. $1 \sim 10$.

Since the two types of modeling are simplified ones, detailed agreement of the wave-forms are not very good and the Peason's correlation coefficients, R, of them are from 0.51 to 0.74. However, the modeling modification from Type-1 to Type-2, by adding balcony, can be found to result improvement of the agreement at several receiving points close to the balcony(See: P3, 5, 6 and 8 in Fig.5). At P8, the value of R changes from 0.51 to 0.70. It is because the point is rather far from the sound source and the effect of side-walls including balconies onto the reflected sound are strong. While, at points 9 and 10, the R values are only slightly improved

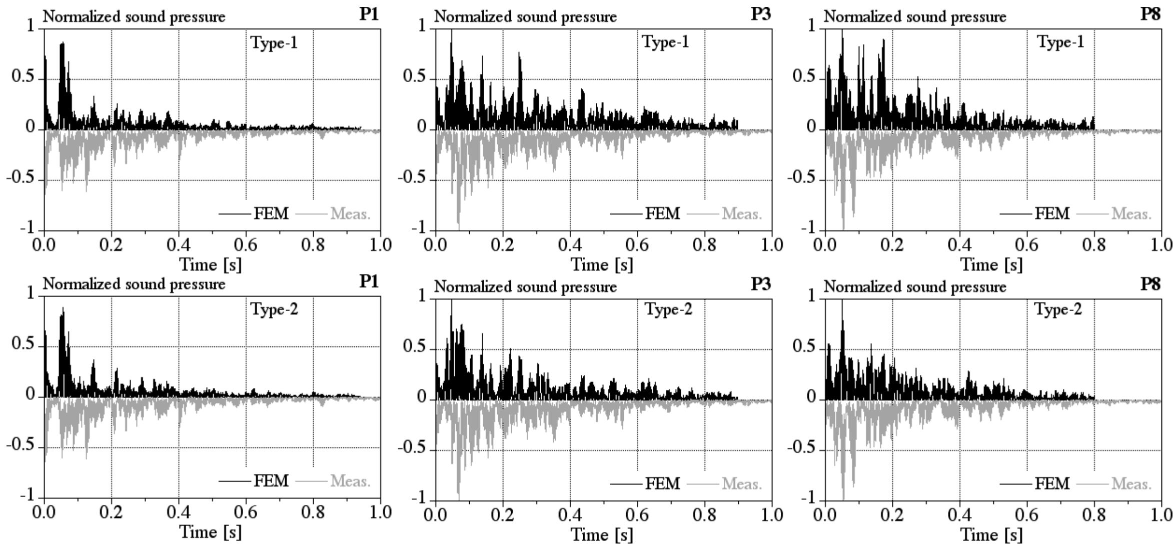

Figure 4. Comparison of sound pressure responses at receiving points P1, 3 and 5 obtained by LsFE-SFA in the time domain with measured data; 1/3 octave band centered at 125 Hz.

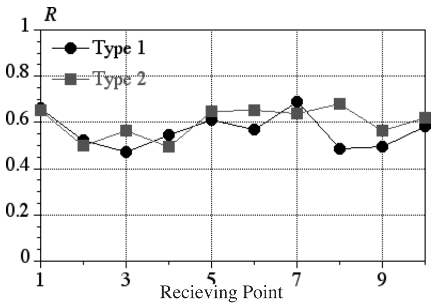

Figure 5. Comparison of Peason's corelation coefficients, R, of sound pressure responses obtained by LsFE-SFA in the time domain with measured data; 1/3 octave band centered at 125 Hz.

because both the points are on the second floor and the effect of balcony is not so much as that at point 8.

4.1. Comparison of Results of LsFE-SFA between Frequency Domain and Time Domain

In the frequency domain, the accuracy of results obtained by LsFE-SFA has been confirmed in many sound fields through the authors' previous studies[1][2]. Here, the results on identical sound fields, Types-1 and -2, obtained by LsFE-SFA in both domains are compared to examine the accuracy of the time domain computation.

To compare the results obtained in different domains, computed sound pressure responses in the time domain were Fast-Fourier-Transformed into the responses in the frequency domain. The comparisons at 63 and 125 Hz are given in Fig.6. All the sound pressures were normalized by the maximum values in each responses and spacial distributions of sound pressure level over the points from No. 1 to 10 were compared.

On the whole, the agreement of the results obtained in the two domains is excellent all over the receiving points from No.1 to 10, and the averaged residuals are 0.8 dB(63 Hz) and 1.5 dB(125 Hz), which confirms the accuracy of LsFE-SFA in the time domain to be good enough

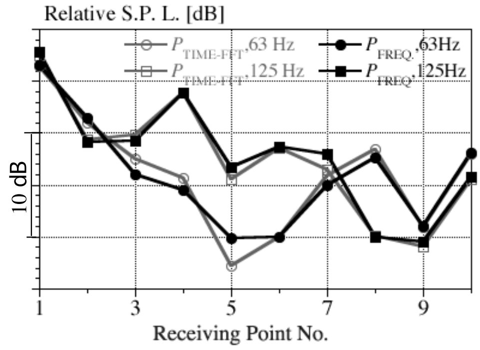

Figure 6. Comparison of sound pressure responses in time and frequency domains. $P_{TIME-FFT}$: SPL given by time-domain computation with FFT, P_{FREQ}: SPL given by frequency-domain computation directly.

as that in the frequency domain.

5. CONCLUSIONS

The authors' time domain LsFE-SFA was successfully applied onto analyses of a multipurpose hall with the volume of 37,000 m^3. The accuracies of results on simplified two models were confirmed by comparing with those obtained by impulse response measurements conducted in the realistic hall. The spacial distribution of Fourier-transformed responses from time domain to frequency domain agreed well with the results obtained by LsFE-SFA in the frequency domain directly, which also confirms the accuracy of LsFE-SFA.

6. ACKNOWLEDGMENTS

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