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Studies on seat dip effect with 3D FDTD modeling

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Summary
According to the literature, the seat dip effect creates a valley in the frequency responses of the direct sound and some early reflections in concert halls. The low frequencies are attenuated up to 20 dB between 100 and 500 Hz due to the sound passing over seating at near grazing incidence. The seat dip effect includes several phenomena due to the wave nature of sound, such as diffraction and scattering. In this paper we simulate several stage and seat configurations with 3D FDTD modeling. The modeling results are shown to be in close agreement with the simulated and measured data presented in the literature. However, the main point of the paper is to analyze and visualize how the low frequency energy is propagating in concert halls. The seat dip effect attenuates the low frequencies of early sound at the listening position despite that the seats are not always absorbing the energy. In fact the energy is directed to other directions and the attenuation of low frequencies in the listening position is only a local phenomenon. The visualizations let us discuss what other consequences of the low frequency sound, redirected by the seats, have to the concert hall acoustics.

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1. Introduction

The seat dip effect attenuates low frequencies of the direct sound and early lateral reflections due to the sound passing at near grazing incidence over audience seating. The effect has been known for over 50 years [1, 2]. These two fundamental articles describe the effects of seat rows with the measured data in the real concert halls and in scale models. The main conclusions in a nutshell are:

- The rows of seats spread the low frequency sound energy in time, thus acting as a sound energy storing mechanism.
- The frequency of maximum attenuation (typically between 100 and 300 Hz) depends on the height of the rows rather than on their spacing. The narrow band maximum attenuation is caused by a vertical resonance between the rows.
- There is also considerable attenuation at wider frequency range (up to 1 kHz), most probably due to the diffractions from the seating rows.
- If the lower part of the seat is removed in order to create the underpass beneath the seats, the maximum resonant frequency is shifted up in frequency.
- The attenuation does not depend markedly on the absorption of the seats. In addition, the attenuation hardly changes if the seats are occupied.

Bradley [3] continued the studies with more measurements in real halls. He found that the seat dip effect is seen already at the third seat row. In addition, he confirmed that the frequency of the main attenuation decreases when the grazing angle increases. Thus, a high stage or inclined audience area does not eliminate the seat dip effect, but they allow to tune the main attenuation to lower frequencies.

Moreover, Davies and Lam [4] have confirmed the main effects of seats by measurements on a real concert hall. In addition, they found that the attenuation could be reduced by adding Helmholtz resonators or vent boxes on the floor below seats. Such additional absorption naturally increases the absorption of the seating area at low frequencies, but also reduces the seat dip effect by absorbing the sound which is delayed due to the seat rows. Therefore, the out-of-phase delayed sound is not interfering with the direct sound and the attenuation in the listening position is reduced. Davies and Lam also showed with scale model measurements that a wide seating area produces more attenuation than a narrow seating area. They speculated that when the seat rows are wider there are more multi-path reflections between seat rows and more diffracted sound components arriving at the listening position. Later, Davies et al. [5] studied the subjective perception of the seat dip attenuation.

1.1. Absorption by audience

Although the seat dip effect attenuates remarkably the sound in the listening position at low frequencies, the sound energy is not absorbed by the chairs and audience. The absorption coefficients of seated audiences presented in the literature [6, 7] are between 0.4 - 0.7 and 0.5 - 0.8 at 125 Hz and 250 Hz octave bands, respectively. Because only about half of the low frequency energy is absorbed, another half is distributed to the hall. As the spacing between seats is typically less than one meter, a wave length equivalent to about 350 Hz, the gap between seats acts as more or less an omnidirectional secondary source. Indeed, Schultz and Watters in their original paper [2] describe in footnote 10 the following observation. At the stage behind the measurement loudspeaker they heard an unchanged pitch, even though the repeated pulses slowly raised in frequency. This unchanged pitch in each hall corresponded roughly to the frequency of maximum seat dip attenuation and may be localized to the seating area.

1.2. Contribution of this article

The observation of Schulz and Watters is interesting and suggests that low frequency energy is reflected partly back to the stage and obviously also to all directions in the hall. This side of the seat dip effect has not been investigated earlier, probably as it is very hard to measure in real halls. However, computer modeling enables such studies and current computers are powerful enough to perform wave-based modeling in spaces of concert hall size. Thus, the contribution of this article is to analyze sound propagation in spaces with audience seating and speculate the other possible, not so well known, consequences of the seat dip effect.

2. Modeling of the seat dip effect

The wave based modeling methods, such as boundary element methods and finite-difference time-domain (FDTD) methods approximate the solution to the wave equation. Thus, the wave phenomena, such as diffraction and interference, are properly modeled and this allows us to study seat dip effect with simulations.

2.1. Related research

Several simulation studies to model the seat dip attenuation and to explain the phenomena have been presented in the literature. Ando et al. [8] were the first to show theoretical calculations. They also first presented the idea to reduce the attenuation by introducing slit resonators below seats. Davies and Cox [9] simulated several seat configurations with a 2-D boundary element method. They interestingly proposed that the attenuation can be consistently reduced by having a one meter deep pit under the seating area. However, such a construction would be quite tricky to realize for large audience areas. An FDTD method was first applied to seat dip modeling by LoVetri et al. [10]. They had a true 3-D simulation and showed that the simulation works well and can predict the measurement data presented earlier in the literature.

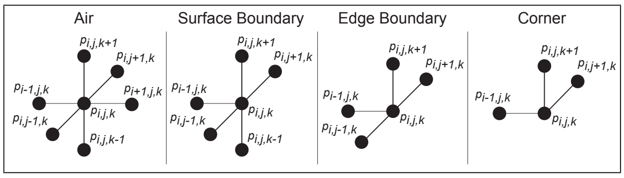

Figure 1. The basic four possible node type combinations of the SRL FDTD scheme.

2.2. Applied 3D FDTD modeling

The FDTD methods are multi-dimensional physical modeling techniques that have been shown to be suitable in room acoustics simulations [11]. In the applied 3D FDTD method, wave propagation is simulated by numerically approximating the spatial and temporal derivatives in the wave equation using second order central finite differences to determine acoustic pressure over a regularly spaced spatio-temporal sampling grid. The calculation of the acoustic pressure at each grid point, or *node*, for each time step is then performed using the resulting update equation. This work is concerned with 3D acoustic modeling and implements the *standard rectilinear* (SRL) FDTD scheme for the following experimentation. In the SRL scheme four basic possible node type combinations exist and are shown Fig. 1.

Using these four node types any 3D arbitrarily shaped convex or concave volume may be represented by a sampling grid of nodes. The update equations for the four node type cases depicted in Fig. 1 are given in (1) air, (2) surface, (3) edge and (4) corner adapted from [12]:

$$\begin{aligned} p_{i,j,k}^{n+1} &= \lambda^2(p_{i+1,j,k}^n + p_{i-1,j,k}^n + p_{i,j+1,k}^n + \\ &\quad p_{i,j-1,k}^n + p_{i,j,k+1}^n + p_{i,j,k-1}^n) + \\ &\quad 2(1-3\lambda^2)p_{i,j,k}^n - p_{i,j,k}^{n-1} \end{aligned} \quad (1)$$

$$\begin{aligned} p_{i,j,k}^{n+1} &= [\lambda^2(2p_{i-1,j,k}^n + p_{i,j+1,k}^n + p_{i,j-1,k}^n + \\ &\quad p_{i,j,k+1}^n + p_{i,j,k-1}^n) + 2(1-3\lambda^2)p_{i,j,k}^n + \\ &\quad (\alpha\lambda - 1)p_{i,j,k}^{n-1}]/(1+\alpha\lambda) \end{aligned} \quad (2)$$

$$\begin{aligned} p_{i,j,k}^{n+1} &= [\lambda^2(2(p_{i-1,j,k}^n + p_{i,j,k+1}^n) + p_{i,j+1,k}^n + \\ &\quad p_{i,j-1,k}^n) + 2(1-3\lambda^2)p_{i,j,k}^n + \\ &\quad (2\alpha\lambda - 1)p_{i,j,k}^{n-1}]/(1+2\alpha\lambda) \end{aligned} \quad (3)$$

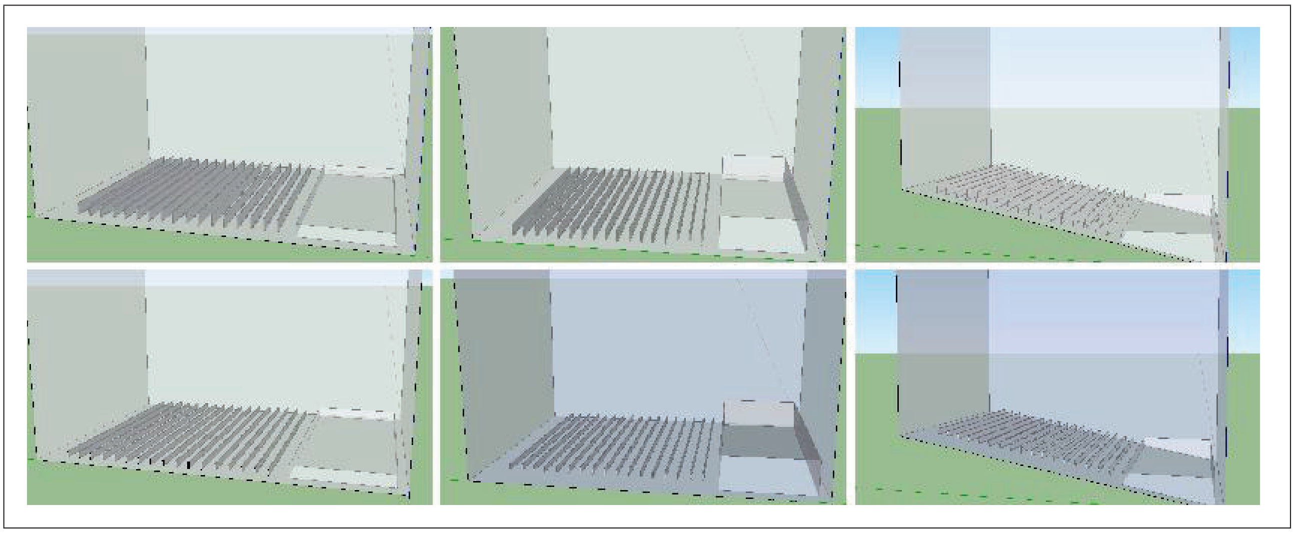

Figure 2. The simulated models, dimensions 30m x 22m x 20m. Top row has seat height of 1.0 m (closed seats) and bottom row 0.5 m with 0.5 m opening for underpass (open seats). For flat floor cases the stage height is even 1.0 m or 3.0 m. Two models have inclining floors (10 degrees) with the stage on 1.0 m height. In all models the spacing between the rows is 1.0 m and the width of the seat back is 0.1 m.

$$\begin{aligned} p_{i,j,k}^{n+1} = & [\lambda^2(2(p_{i-1,j,k}^n + p_{i,j,k+1}^n + p_{i,j+1,k}^n) + \\ & 2(1-3\lambda^2)p_{i,j,k}^n + \\ & (3\alpha\lambda - 1)p_{i,j,k}^{n-1}]/(1+3\alpha\lambda) \end{aligned} \quad (4)$$

where $p_{i,j,k}^{n+1}$ denotes the acoustic pressure at the future time step $n+1$ at position ijk. Then α is a free numerical parameter, between 0 and 1, used to weight the boundary impedance. When $\alpha = 0$ and $\alpha = 1$ the boundary is totally reflective and almost anechoic, respectively. Parameter $\lambda = \frac{cT}{X}$ is called the Courant number and X is the unit grid spacing and T the unit time step, for this work $\lambda = 1/\sqrt{D}$. Setting $T = 1/f_s$, the metric spacing between the nodes is related to the sampling rate f_s of the grid as

$$dx = \frac{c}{\lambda f_s} \approx \frac{344 \cdot \sqrt{3}}{f_s} \quad (5)$$

where dx is the distance in meters between two nodes and c is the speed of sound in m/s and D is dimensionality.

2.3. Studied models

In this study, six simple concert hall models were simulated, see Fig. 2. The dimensions of the halls were 30 m x 22 m x 20 m. As $D = 3$ and $f_s = 7000$ Hz were used, the internodal distance was $dx = 0.0851$ m, resulting in the 3D mesh of 352 x 259 x 235 = 21,424,480 nodes. The boundaries have all the same wall impedance weighting of $\alpha = 0.1$, representing quite hard material. The models were designed with Google SketchUp. The meshing and simulation of one model took about 30 minutes in total. It should be noted that only one simulation is needed for each model because the impulse responses of all receiver nodes of interest are stored simultaneously. The studied receiver positions were in three piles at the center axis at 15, 20, and 25 m from the back wall of the stage. In other words, they were above row numbers 6, 11, and 15. The height of nine receivers in each pile were between 1.19 and 2.55 m above the floor level. The omnidirectional impulse source was at the center axis, 7 m from the back wall of the stage, and 1.0 m above the stage floor in all models.

3. Results

The applied FDTD simulation suffers from the direction dependent dispersion due to the rectangular mesh. Therefore, simulation is almost error free up to about $0.1f_s$, in this case up to 700 Hz. However, that frequency range is enough to study the seat dip effect. As the attenuation is at low frequencies the analysis window should be as long as possible. Here, 15 ms after the direct sound can be windowed in each receiver position, before the first reflection. Figure 3 shows visually the 15 ms time window after the direct sound used in the following analysis.

First, the hall with 1.0 m high seating attached to the flat floor (closed seats) was simulated and the nine frequency responses in all receiver positions are found in Fig. 4. The seat dip attenuation is clearly seen in all positions and the frequency of the main dip is behaving as presented in the literature: the frequency is about 1/4 wavelength of the high of the seat (i.e. 86 Hz) and the frequency of the dip is decreasing when the height of the receiver is increasing. In addition, the attenuation at higher frequencies is also clearly seen.

Second, frequency responses of nine receivers in position 2 in all six studied halls are seen in Figs. 5

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and 6. Figure 5 reveals that the attenuation is on the narrower frequency range when the grazing angle increases, i.e., the stage is higher. However, with the inclining floor the grazing angle is also bigger than with the large floor, but the seat dip attenuation is similar to the flat floor and low stage case. When the seating is "open", enabling underpass of the sound, the main attenuation frequency is shifted about one octave higher, but the wider band attenuation up to 800 Hz remains roughly the same. Thus, with such seating the main attenuated frequency is at 1/2 wavelength resonance of the seat height.

3.1. Attenuation without the direct sound

As the FDTD modeling is performed with hardly any absorption on the boundaries, the seat dip attenuation is proved to be the interference of the direct sound and delayed multiple copies of it. The modeling makes it possible to study the delayed sound in great detail, because the direct sound can be removed from the simulations. Due to long wavelengths of low frequencies the direct sound cannot be windowed out in time. But, if the simulation is performed without both seating and floor, the direct sound with diffraction from the stage edge can be removed by subtracting the "free field case" from the "seated case" as illustrated in Fig. 3.

Figure 7 shows the frequency responses of the cases of Fig. 5 without the direct sound. It is seen that the main attenuation dip has disappeared and the frequency responses are relatively flat, except in position 1. In addition, the receiver height has quite small effect as all the nine responses in each receiver position are close to each other. Therefore, it could be concluded that the sound waves that have diffracted between the seats are reflected back from the floor and directed to all directions. The visualization in Figs. 3 and 9 indeed show the spherical waveforms filling the space after the direct sound.

In other hall models the frequency responses without the direct sound appear similar, as plotted in Fig. 8. The energy is not attenuated much as it has almost the same amount of energy as the direct sound. Moreover, this energy is directed to the upper half of the hall. In addition, the energy is not greatly attenuated at the higher receiver positions suggesting that the seated audience area is acting as a kind of secondary area source.

4. Discussion

The simulation confirmed that the seat dip effect is caused by delayed sound interfering with the direct sound. The 3D FDTD simulation could predict the effects presented in the literature with other simulation methods and measurements in real halls. As a novelty, it was found out that the delayed interfering sound is

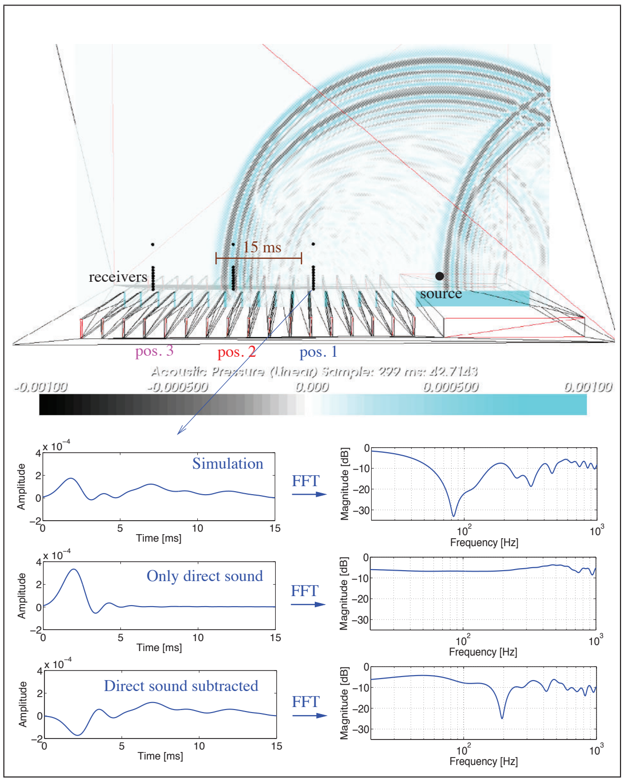

Figure 3. The visualization of one simulation. The halls were also simulated without seating and floor to obtain only the direct sound with diffraction from the stage edge. Finally, the direct sound can be subtracted from the original simulation to see the contribution of seats.

directed up which might have some perceptual consequences. If the hall is small with low ceiling the sound energy redirected by the seats might reach the listeners quite early and at a considerable level. Based on our informal listening and the recent analysis of frequency responses over time [13] this seems to be the case in some small concert halls. The delayed low frequencies render the sound muddy and the articulation of bass instruments is obscured. In fact, Bradley [14] has been thinking similarly: "increasing low frequency sound levels by reducing the amount of low frequency sound absorbing material in the hall is not likely to compensate for the large reductions in low frequency early arriving sound." The proper perceptual evaluation remains as future work. Another future study would be to simulate other seating designs to reduce the seat dip effect as much as possible.

Acknowledgement

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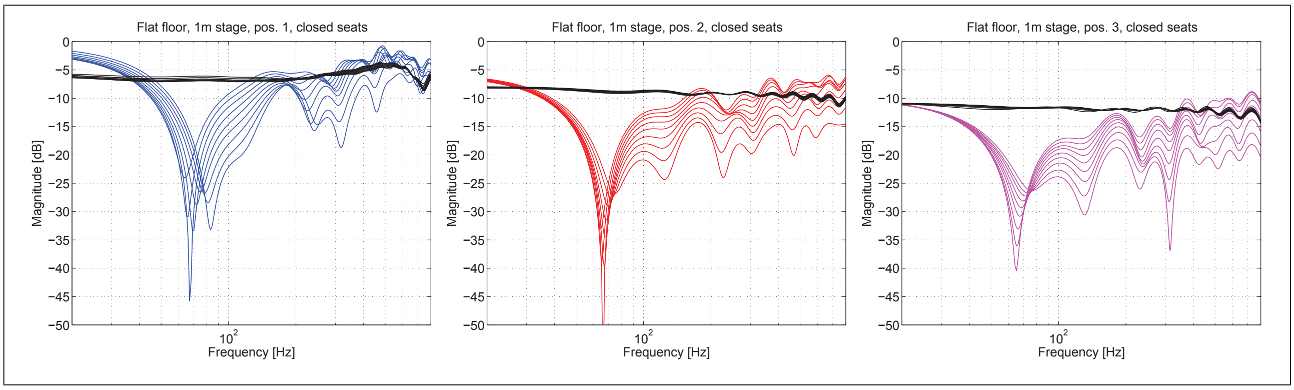

Figure 4. Frequency responses in the 9 receivers at position 1 (blue, left), position 2 (red, middle), and position 3 (magenta, right). In each figure, the direct sound with stage edge diffraction is plotted with black lines.

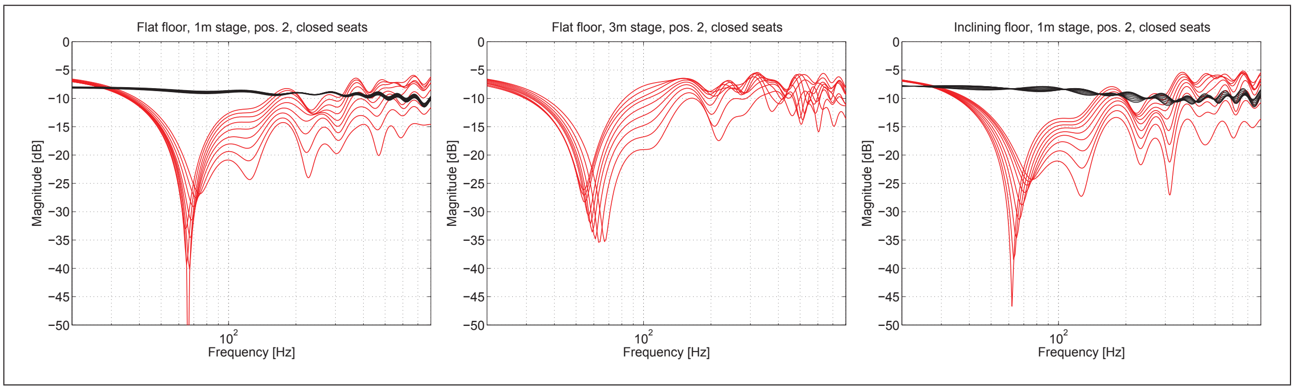

Figure 5. Frequency responses in the 9 receivers at position 2 with 1.0 m high seating. Stage height 1.0 m, flat floor (left), stage height 3.0 m, flat floor (middle), and stage height 1.0 m, inclining floor (right). The direct sound with stage edge diffraction is plotted with black lines.

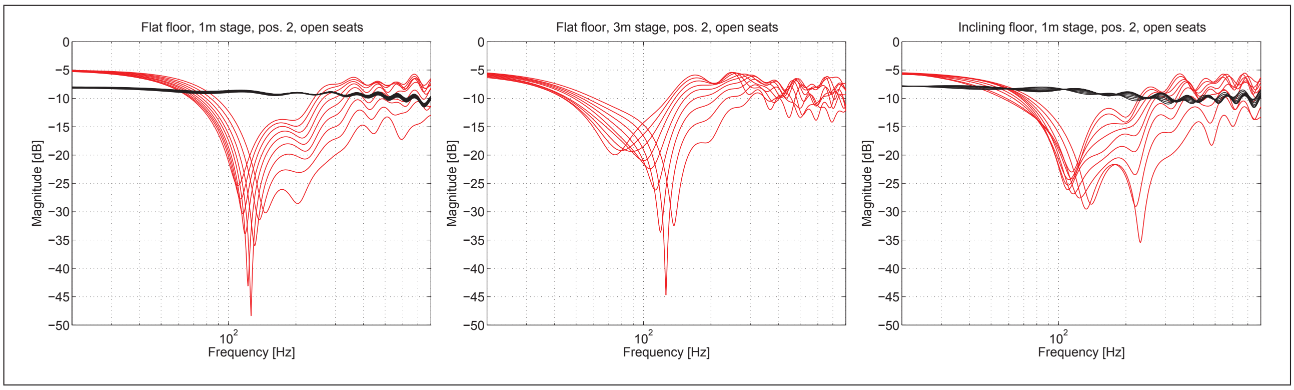

Figure 6. Frequency responses in the 9 receivers at position 2 with 1.0 m high seating with underpass (0.5 m). Stage height 1.0 m, flat floor (left), stage height 3.0 m, flat floor (middle), and stage height 1.0 m, inclining floor (right). The direct sound with stage edge diffraction is plotted with black lines.

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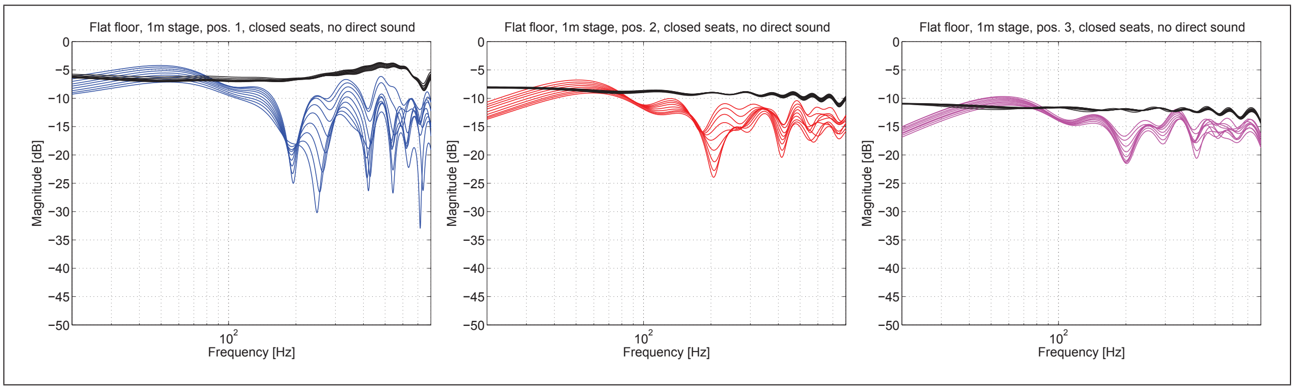

Figure 7. Closed seating, flat floor, no direct sound, all receiver positions.

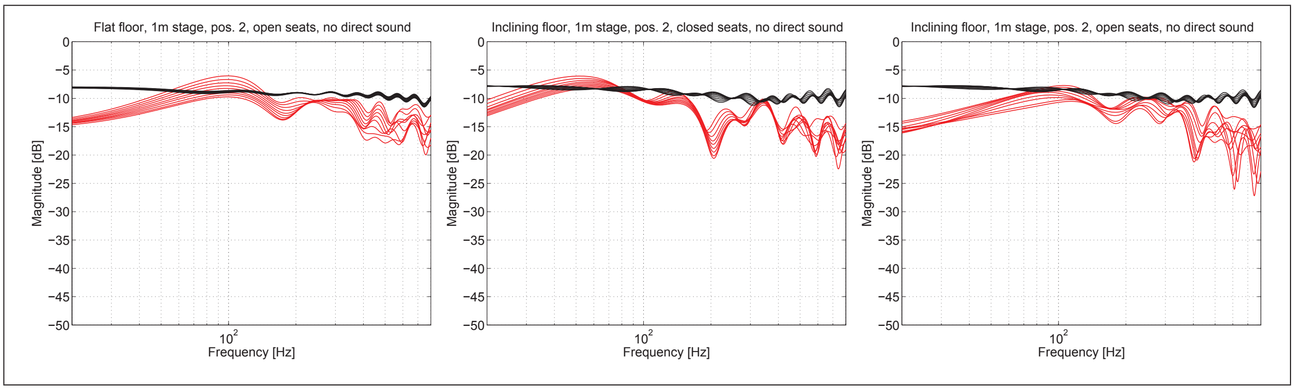

Figure 8. Open seating, flat floor, no direct sound, all receiver positions.

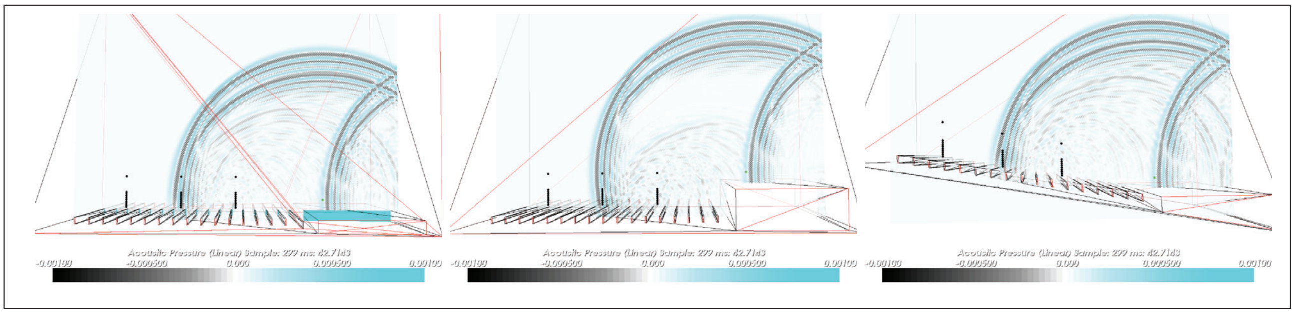

Figure 9. Screen shots of the FDTD simulations with open seats in three studied concert hall models.

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