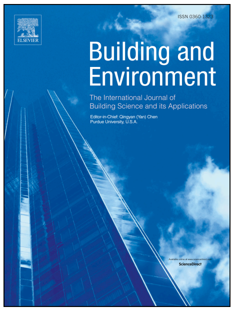

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Acoustic modeling of sequential spaces: a parametric study

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Abstract

Sound field modelling of sequential spaces is required for large-scale public buildings. A FEM model comprising five successive rooms was used for a parametric study considering, i.e., contextual (opening dimension and position, number of rooms), acoustical (absorption coefficient and position) and source (directional radiation of opening and additional source) factors. The results reveal that (i) In rooms with high absorption, the average SPL of the rooms is higher, and the level difference between rooms is smaller with a larger opening dimension. Opening position only has impact for rooms with low absorption. (ii) The level differences between rooms are larger for oblique radiation compared to horizontal radiation, especially for rooms close to source. With an additional source (e.g., HVAC system and human speech) in a room, the level in this room is kept or reduced by approximately 10 dB with increasing opening dimension for rooms with high or low absorption, whereas the levels in other rooms increase for rooms with high absorption. (iii) The changes achieved by absorption are more significant with low absorption. The difference in the SPL between uniform and non-uniform absorption distribution with a given absorption amount is greater with a smaller opening dimension. (iv) The effects on the SPL in the first receiving room, caused by adding more sequential rooms, is less when the absorption in those rooms is high (e.g., with an absorption coefficient of 0.5), and the difference between different absorption coefficients is about 6 dB maximum, depending on the number of rooms.

Keywords

acoustic simulation; sound field modelling; parametric study; finite element method; sequential spaces; coupled rooms

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1. Introduction

Sound field modeling in sequential spaces (i.e., spatial systems consisting of multiple spaces connected by an opening in between) is necessary for noise control and acoustical design. Large-scale public buildings (e.g., museum/exhibition spaces, shopping malls, and transportation hubs) adopt such spatial forms to provide continuous functional space and facilitate movement of individuals/visitors. The research in this area is relatively rare because the acoustics of non-performing spaces are not considered important and the development of tools in real and virtual acoustics is limited. Although current research in this area has been conducted using objective [[1]–[4]] and subjective [[5]–[7]] approaches, these acoustic programs [8] were reported in the absence of further details concerning spatial and source information in the context of sound attenuation across the spaces. Therefore, the fundamental strategies that should be used to achieve target performance of the sound field, especially in the design phase, remain unknown to professionals.

Various room acoustics studies of coupled spaces have been conducted to explore how to use contextual and acoustical factors to adjust the degrees of coupling effects under different assumptions and constraints. Regarding the contextual factors (e.g., opening dimension and position), Harris and Feshbach studied how the dimension and position of the opening between two coupled rooms affected the frequency, using the wave approach [9]. Meissner investigated the effects of mode degeneration and localization in coupled rooms by assuming low absorption, which led to weakly coupled modes [10]. Based on the field eigenfunction representation, Poblet Puig and Rodrıguez-Ferran analyzed the sound transmission through the openings between cuboid-shaped rooms and proposed that the opening position and room dimensions are crucial to the coupling effects between the rooms [11]. For the acoustical factors (e.g., absorption coefficient and position), Fitzroy presented an empirical expression considering non-uniform absorption in the three orthogonal directions of rectangular rooms with several measurements [12]. By modeling a rectangular room with one absorption wall, Maa showed that absorption depends not only on the absorptive material, but also on its position and on the room shape [13]. McMullan [14] noted out that the absorption provided by absorption materials significantly affected on the sound quality (acoustics) within a room but had little effect on the amount of sound passing in or out of a room (sound insulation). These studies, although limited to spaces of two coupled rooms, demonstrated the potential of parametrization of both contextual and acoustical factors to modify the sound field. However, the efficiency of such techniques in controlling the sound passing across several rooms remains to be determined.

For effective prediction in coupled rooms studies, techniques such as finite element method (FEM), geometrical acoustics, and the diffusion equation have gradually become more acceptable and accurate in computational simulation. An energy-based modeling approach was investigated by Shi et al. [15], where coupling was achieved by the continuity of the exchanged power between the rooms and then validated by comparison with the results of the FEM. Geometrical acoustics-based simulations have also been validated [16]. Jing and Xiang produced a visualization of the sound pressure distribution and sound energy flow across the coupling aperture of two rooms using diffusion modeling [18]; Billon et al. developed a numerical diffusion model to predict the spatial variations of the sound pressure level (SPL) [19]. Various numerical methods [[20]-[23]] and analytical models [[24]-[28]] are utilized to determine the acoustic quantities of interest of the opening. FEM is a routinely used tool for most acoustic studies [21]. The ray and beam tracing methods can be applied to spaces with arbitrary shapes, which are empty or furnished. The sound field is supposed to be comprised of noninteracting sound rays reflected by surfaces with surface dimensions much larger than the sound wavelength. However, the accuracy of these methods for large source–receiver distances or complex boundary conditions has been proven to be insufficient [[29], [30]].

In building engineering, to control the radiated noise level, plane waves can be used to simulate sounds in the far field, e.g., outdoor noise incident across the window at the façade of the building as surface transportation noise (e.g., busy highway) is usually modelled as an incoherent line source [31]. This is akin to the indoor noise coming from other rooms far from the investigated space (e.g., a crowd). As the acoustic opening attenuates the noise coming from different dominant incidence angles (e.g., traffic noise on the upper floors of high-rise buildings or crowd noise from a source room with oblique boundaries), the performance could be investigated with different noise source incidence angles of the plane wave. For instance, an incidence angle of 60° corresponds to an approximate position on the 20th floor of a building from a road, at surface level, 50 m away from the building [32]. In addition, there are additional noise sources (e.g., HVAC systems and human speech) in large-scale public spaces (e.g., museums), which are frequently simplified as omnidirectional or directional point sources in predictions, whose effects at a particular location or area must be considered.

Consequently, parametric research is based on case studies. Compared with other well-established room acoustics programs, FEM could better consider the effects of diffraction, which is essential in sequential spaces. The results could be used as reference information in practical applications, especially during the design phase of sequential spaces, by providing relevant case studies. In-situ measurements were conducted in selected exhibition spaces to confirm the accuracy of the predictions by validating the results of FEM. The aim of this research was to explore the prediction efficiencies of both contextual and acoustical factors on performance of sound attenuation through the rectangular openings in sequential spaces using parametric studies, i.e., opening dimension and position, absorption coefficient and position. In addition, the effects of source factors were investigated with directional radiation of the opening and additional source. Lastly, the influence of increasing the number of rooms to enlarge entire space scale was analysed.

2. Methods

2.1. Simulation configuration

The simulations were conducted with the FEM software COMSOL Multiphysics. The density of the mesh was set to provide a minimum of six elements per wavelength at 4 kHz for all frequencies tested (≤ 4 kHz) to ensure consistency as well as accuracy. Perfectly matched layer (PML) [22] absorbing boundary conditions were adopted to compute the acoustic resonances in 3D open cavities with other general boundaries. The air aperture of 3D open cavity could be theoretically considered as an equivalent structural component with a small thickness, neglecting the physical properties of the opening [26]. However, the 3D model would need more than 120 million elements, making it highly time consuming to provide the required physical insight and practical guidelines. The 2D model runs reasonably well for various geometrical conditions and covers a higher range of frequencies with a feasible modeling efficiency.

Figure 1 illustrates the 2D model as a cross-section containing five rectangular rooms with initial dimensions of width w_{sp} = 5.0 m and length l = 8.0 m separated by solid walls with rigid boundary conditions and connected by openings of width w_{op} = 2.0 m. The ratio of the width of these openings to the width of the entire separating partition is d_{op} = 40%, and the openings are located in the middle of each separating partition. The openings on the end walls on the left and right sides are enclosed with PMLs to emulate a free-field condition. The thicknesses of all separating partitions are set to 0.2 m, because this value is close to that normally used in practice. The noise incidence at the opening of the separating partition is assumed to be plane waves with an initial incidence angle of $\theta = 0°$, indicating the far-field source information (e.g., the noise impinging on the opening is at the same level of the investigated spaces).

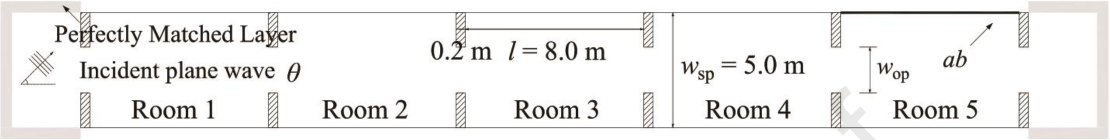


Fig. 1. (Color online) 2D FEM computational model (in m).

2.2. Simulation parameters

As discussed in Section 1, the performance across the spaces was investigated based on three aspects considering, i.e., contextual (opening dimension and position, number of rooms), acoustical (absorption coefficient and position) and source (directional radiation of the opening and additional source) factors.

For the contextual factors, one of the parametrizations is the opening/partition area ratio d_{op}, which is defined as follows:

$$d_{op} = w_{op}/w_{sp} \tag{1}$$

where w_{op} is the width of the opening and w_{sp} is the width of the separating partition. This value ranges from 0% to 100% to meet all possible conditions, ranging from a small opening to an opening spanning the entire width of the separating partition. d_{op} value of 20% and 40% indicate small and large openings, respectively. Another parametrization is the opening/partition position ratio p_{op}, which is defined as follows:

$$p_{op} = (1-d_{op})/2 \tag{2}$$

This value ranges from 0% to $(1-d_{op})/2$. The value of 0% indicates that the opening is in the middle of the separating partition, and the maximum $(1-d_{op})/2$ means that the opening is on one side of the separating partition attached to the side wall along the length of the rooms. In the case of the number of rooms across the spaces, it is parameterized with N. The range of N investigated in this study is 1−10.

For the acoustical factors, one parametrization is the absorption coefficient ab applied uniformly to the boundaries of each room, which ranges from 0 to 1.0. The values of 0.01 and 0.5 are defined as low and high room absorption, respectively.

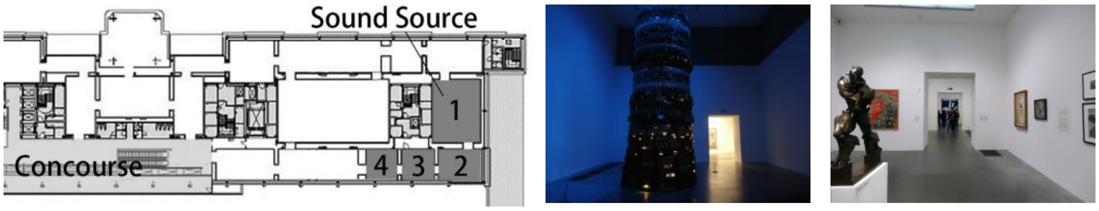
Another parametrization is termed as “absorption position” in this research, for which the absorption distribution on the boundary is presented either uniformly or non-uniformly (along the sound attenuation).

For the source factors, one parametrization is the directional radiation of the opening, i.e., the incidence angle θ of the transparent boundary. Oblique noise incidences cases are analogous to noise impinging on the openings at different floors of the building, e.g., an incidence angle of 60° corresponds to an approximate position on the second floor of the building when a walkway is on the first floor, 5.0 m away from the wall of an atrium. Two values of the incidence angle θ, 0° and 60°, were investigated in this study. Another parametrization is termed as “directional radiation of additional source,” where an omnidirectional and directional point source is placed in the corner of Room 1.

2.3. Validation of the simulation

2.3.1. In-situ measurement

The simulation results were validated by comparing them to the in-situ measurements from selected rooms in the Tate Modern, London, United Kingdom, which was also the case site of the preliminary study [33]. As shown in Figure 2, the site features a large-scale cylindrical artistic sound installation “Babel, 2001”, which emits a mixture of music and voices as the primary source. A large auditorium-like space is the source room (Room 1), which is connected to three normal exhibition spaces exhibiting modern art drawings hung on flat walls without fine decorations, acting as the receiving rooms (Rooms 2, 3, and 4). The dimensions of the investigated spaces are as follows: the height of Room 1 is approximately twice that of the successive rooms, which is approximately 4.7 m; the widths and lengths of Rooms 3 and 4 are approximately 6.3 m; and the length of Room 2 is slightly larger than that of Rooms 3 and 4.



(a) (b)

Fig. 2. (Color online) Configurations of the case site in the Tate Modern. (a) floor plan: sound source and location of each room and (b) site photo of the source room (left) and receiving rooms (right).

To obtain the sound attenuation across the openings in each investigated room, a sound level meter (NTi XL2) was set in the center of each room at the height of 1.65 m above the ground under the unoccupied condition of the museum (visitors were not present). These measured results were also verified with HEAD acoustics SQobold. The measurements were taken three times on different days, and the values in each room were averaged.

2.3.2. Simulation method

The 2D FEM computational model was built according to the actual spatial dimensions, as illustrated in Figure 3b. The boundary conditions for a given space were specified considering its relation to the subsequent spaces, otherwise the sound energy would be much larger if it is considered as an enclosed space because of the reflections. Moreover, because the height of Room 1 is not comparable to those of Rooms 2, 3, and 4, the boundary conditions of Rooms 2, 3, and 4 were set, and the area representing the source room with “Babel, 2001” and the other spaces of the museum, which are not detailed at this stage as they were not under investigation, were bounded with PMLs. To simulate the reflected sound in the source room (Room 1) attenuating across the opening between the source room and adjacent receiving room (Room 2), noise incidence at the separating partition was assumed to be a plane wave with $\theta = -90°$. The opening was located, slightly toward the side wall rather than in the middle of the separating partition in the initial plan. The value of *ab* was initially set to 0.02 to match the low room absorption due to the indoor environment, which was composed of smooth, painted concrete and glass.

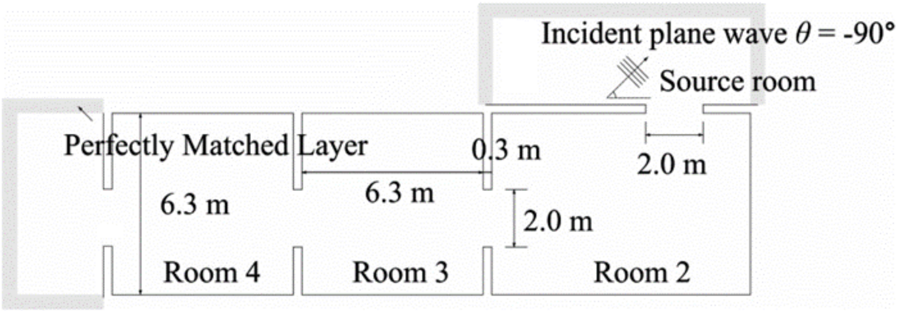


Fig. 3. (Color online) 2D FEM validation model (in m).

2.3.3. Comparison between measurement and simulation

Figure 4 shows the normalized results of the average SPL of each room obtained by the in-situ measurement and computational simulation. The two sets of results consistently match across a range of frequencies. Therefore, it can be concluded that the attenuation of sound caused by the primary source or background sound in practice across the rectangular openings could be simulated. To examine the sensitivity of room absorption, two conditional values of *ab* (0.01 and 0.03) were tested. It was determined that the attenuation of the sound level of each room was almost the same for the two investigated values of *ab*, with the difference limited to 3.0 dB. In particular, the results corresponding to *ab* = 0.01 and 0.02 are closer to the real condition than those corresponding to *ab* = 0.03.

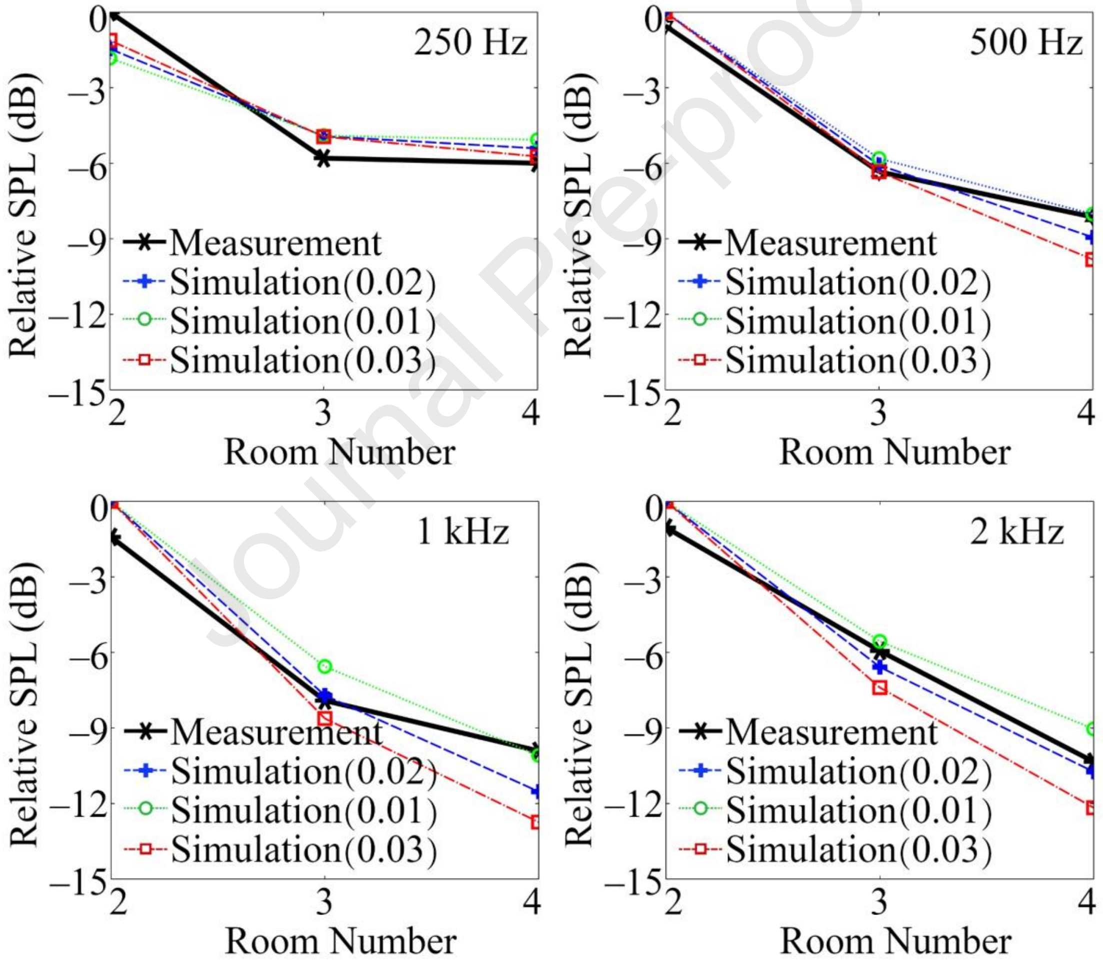


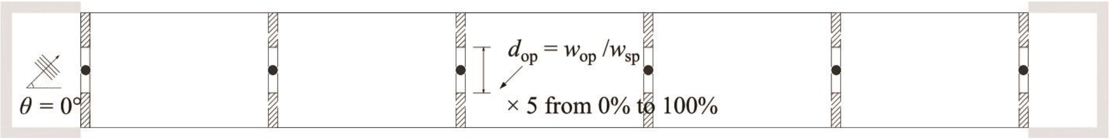
Fig. 4. (Color online) Comparisons of the validation results at a range of frequencies.

2.4. Simulation experiment

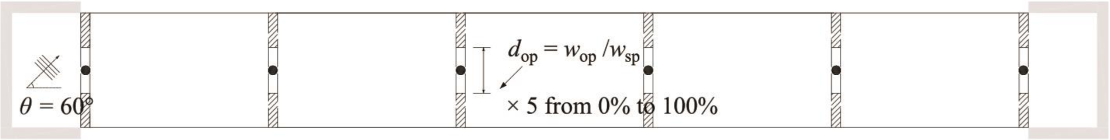
The underlying research questions were to be addressed according to the parametrizations stated earlier, and the efficiency of the parametrizations in performance adjustment of the sound field across the spaces were investigated by conducting six comparative studies: (1) Study 1 (opening dimension): parametric d_{op} ; (2) Study 2 (directional radiation of the opening): parametric d_{op} when $\theta = 0°$ or 60°; (3) Study 3 (directional radiation of additional source): parametric d_{op} when an additional source is applied; (4) Study 4 (opening position): parametric p_{op}; (5) Study 5 (absorption coefficient): parametric *ab* with two d_{op} = 20% and 40%; (6) Study 6 (absorption position): parametric *ab* with non-uniform absorption distribution; and (7) Study 7 (number of rooms): parametric N. Table 1 shows the simulation input used in COMSOL, and Figure 5 shows the experimental configuration of each study. Note that all the openings and walls in the model, which are marked with the circles and broad-brush lines, respectively, were changed simultaneously in each simulation.

Table 1. Three parametrizations (i.e., contextual, acoustical and source factors) and simulation input in COMSOL.

Study		**Contextual factor**			**Acoustical factor**		**Source factor**	
		Opening/partition area ratio d_{op}	Opening/partition position ratio p_{op}	Number of rooms N	Absorption coefficient ab	Absorption position [-]	Angle of opening incidence θ	Directional radiation of additional source [-]
1	a b	0% – 100%	0%	5	0.01 0.5	Uniform	0°	No
2	a b	0% – 100%	0%	5	0.01 0.5	Uniform	60°	No
3	a b	0% – 100%	0%	5	0.01	Uniform	0°	Omni directional
	c d	0% – 100%	0%	5	0.5	Uniform	0°	Directional
4	a b	40%	0% – $(1-d_{\mathrm{op}})/2$%	5	0.01 0.5	Uniform	0°	no
5	a b	20% 40%	0%	5	0 to 1.0	Uniform	0°	no
6	a	20% 40%	0%	5	0 to 1.0	Non-uniform	0°	no
7	a b	40%	0%	1 – 10	0.01 0.5	Uniform	0°	no

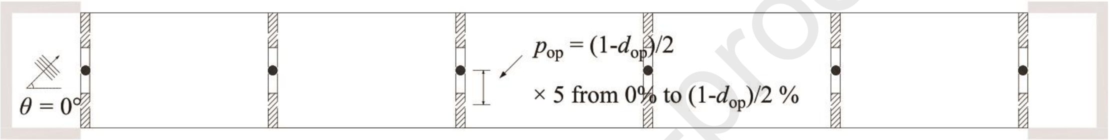


(a) Opening dimension

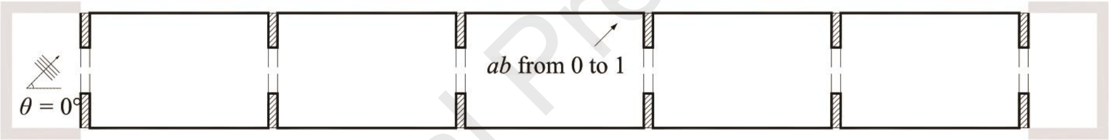


(b) Directional radiation of the opening

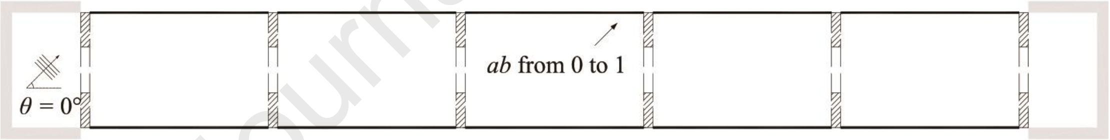
(c) Directional radiation of the additional source



(d) Opening position



(e) Absorption coefficient



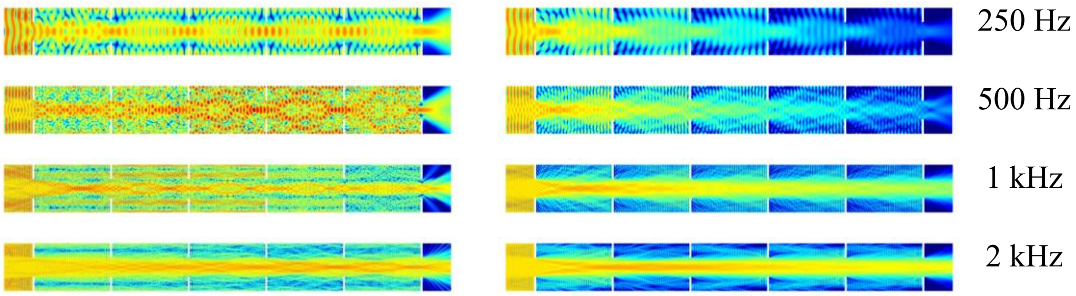
(f) Absorption position

Fig. 5. (Color online) Experimental plans of (a) Study 1: opening dimension; (b) Study 2: directional radiation of the opening; (c) Study 3: directional radiation of the additional source; (d) Study 4: opening position; (e) Study 5: absorption coefficient; and (f) Study 6: absorption position.

3. Results

3.1. Effect of opening dimension

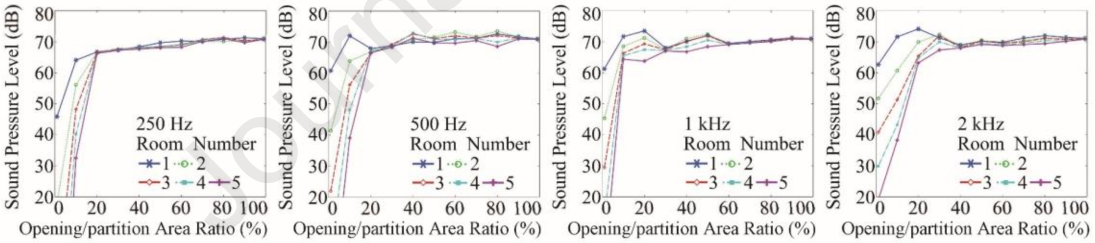
Figure 6 visualizes the SPL distribution for example simulations of the initial model (i.e., d_{op} = 40%) at a range of frequencies for *ab* = 0.01 and 0.5. The sound attenuation across the spaces exhibits different patterns, and the transmitted field on the right side is reduced in a clearly different manner from 250 Hz to 2 kHz.



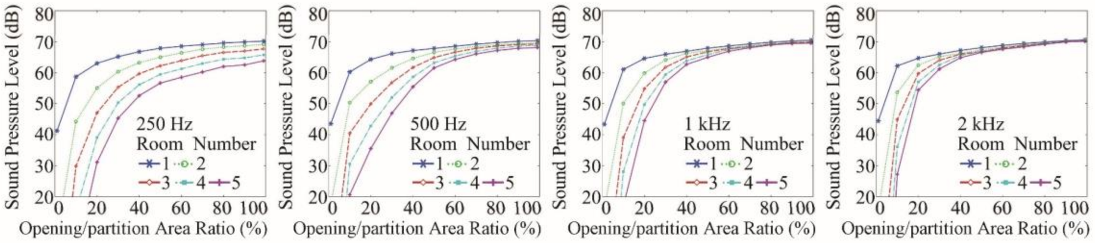
(a) (b)

Fig. 6. (Color online) Sound pressure distribution. (a) *ab* = 0.01 and (b) *ab* = 0.5.

Adjusting the opening dimension could be one of the most direct ways to control the sound attenuation by modifying of contextual factors. To understand the effect of the opening dimension under two acoustic absorption conditions, i.e., low and high absorptions, were defined as *ab* = 0.01 and 0.5, respectively. Figure 5a shows the experimental plan for this study, and Figure 7a and 7b show the average SPL of each room from 0% to 100% d_{op} for the two *ab* values. The results reveal that the sound field pattern imposed by the parametric d_{op} is inconsistent under the conditions of low and high *ab*, indicating that when adjusting the value of d_{op} in the design phase, it is necessary to consider room absorption conditions.



(a) *ab* = 0.01



(b) *ab* = 0.5

Fig. 7. (Color online) Average SPL of each room for d_{op} values from 0% to 100% for two *ab* at $\theta = 0°$. (a) *ab* = 0.01 and (b) *ab* = 0.5.

In the case of low room absorption, as shown in Figure 7a, the average SPL of each room attenuated with increasing source–receiver distance, i.e., the levels decreased from the highest in Room 1 to the lowest in Room 5, up to a certain value of d_{op}. The level differences between the rooms were large at low d_{op} whereas at high d_{op} values, they were very small, as expected. This value of d_{op} after which the levels became unpredictable was smaller at lower frequencies, e.g., 20% d_{op} at 250 and 500 Hz and 40% at 2 kHz.

However, the average SPL of each room corresponding to the increasing d_{op} seemed to increase until a certain value of d_{op} and then decrease in an unpredictable pattern until the discussed value of d_{op} when the levels were identical across the spaces. Moreover, the level differences were unrelated to the d_{op}, which could be owing to coupling effects between the rooms, i.e., strong, medium, and weak. For a low room absorption and small opening (d_{op} = 0% – 20%), the coupling effect is weak, i.e., the spaces are acoustically separated with limited sound flowing back, and the non-diffuse sound field is confined to the area near the opening; therefore, even a small change in opening dimension could result in significant differences in the sound levels. On the other hand, for a large opening (d_{op} > 60%), the separated spaces act as a single space, and any change in the opening dimension does not affect the sound levels significantly. In addition, if the opening dimension is in the medium range (d_{op} = 20% – 60%), the non-diffuse sound field near the opening area could be the largest compared to those of the small and large openings.

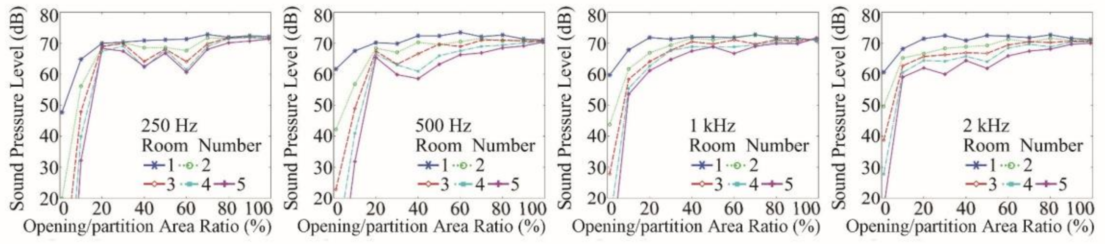
As shown in Figure 7b, in the case of high room absorption, the levels of each room clearly attenuated from the highest to lowest from Room 1 to Room 5, and the values gradually increases with increasing d_{op}. The patterns were similar at all frequencies. The level difference between the rooms gradually kept decreasing before stabilized. For increasing d_{op}, the efficiency required to reach the stable value was greater at higher frequencies than at lower frequencies. The reason could be that as d_{op} increased, the sound flowback from the other side of the spaces decreased. Once d_{op} reached a certain value, the levels were no longer affected by the d_{op}, and the separating partition could be regarded as acoustically transparent. For a high room absorption, the distribution of sound energy became more uneven with increasing d_{op}, and the attenuation in the sequential rooms became more rapid and closer to that in the free-field condition.

It is interesting to note that similar results were obtained with a smaller room length (l = 5.0 m), which is not presented here. With decreasing area, d_{op} value required to reach the stable value became smaller for all frequencies.

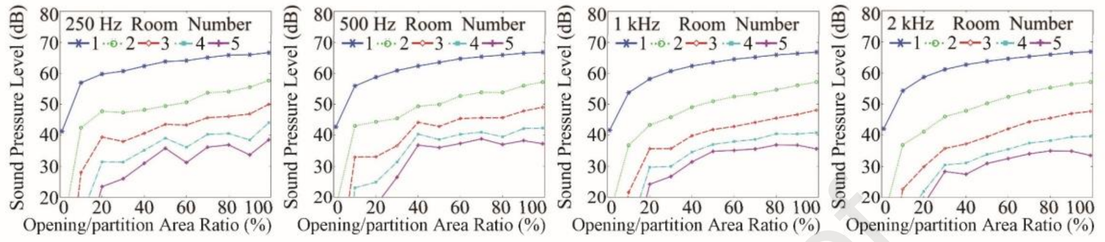
3.2. Effect of directional radiation of the opening

An incidence angle of $\theta = 60°$ was defined to simulate the sound field when the source and receiving room are not at the same level, e.g., for a room on the second floor near an atrium. Figure 5b shows the experimental plan for this study with a parametric d_{op} value to examine the effects of the oblique incidence angle of the opening as the dominant directional radiation of the opening.

Figures 8a and 8b show the results corresponding to those in Figures 7a and 7b, for an incidence angle of $\theta = 60°$. The results reveal that the level of Room 1 remained the same as in the previous study, while those of Rooms 2, 3, 4, and 5 decreased considerably. The differences between low and high absorptions were more significant at $\theta = 60°$. In the case of low absorption, as shown in Figure 8a, the levels at $\theta = 60°$ were still random but clearly attenuated from Room 1 to 5. The level differences were larger than those at $\theta = 0°$ at all frequencies. In the case of high absorption, as shown in Figure 8b, the phenomenon of the level increasing with d_{op} and the level difference decreasing to a stable value are shown, similar to the results of a previous study. However, the stable values increased, e.g., close to 10.0 dB rather than 0 dB at $\theta = 0°$. The level difference near the source was particularly significant because of the direct sound component. Therefore, the coupling effect was more observable at $\theta = 60°$. Especially under the condition of low absorption for the medium range of the opening dimension, the level differences were significant indicating a more obvious non-diffuse sound field near the opening. Additionally, the level differences under the condition of high absorption were larger.



(a) ab = 0.01



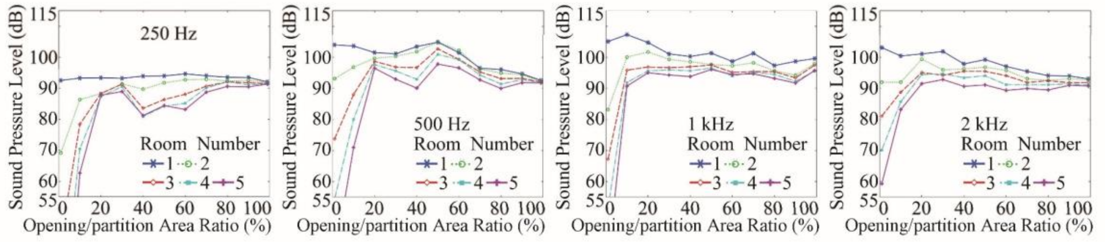
(b) ab = 0.5

Fig. 8. (Color online) Average SPL of each room for d_{op} from 0% to 100% with two ab at $\theta = 60°$. (a) $ab = 0.01$ and (b) $ab = 0.5$.

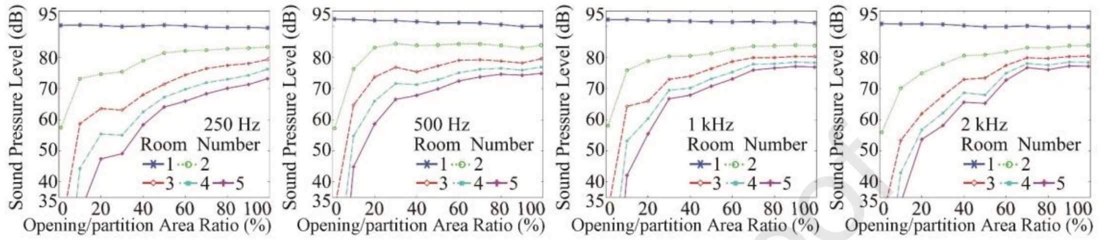
In regard to the dominant directional radiation of the opening, it was concluded that for both low and high room absorption, the level difference between rooms was consistently larger when the source room was located at a higher level than the receiver room rather than at the same level, which meant that there was a larger sound attenuation across the spaces. The level difference between rooms was significantly higher for the room closer to the source opening compared to the successive level differences between rooms. This tendency was not observed when the source and receivers were located on the same level, indicating a distinguishable gap in listener perception (e.g., loudness) between the source and first receiving room.

3.3. Effect of directional radiation of the additional source

To study the effect of additional omnidirectional or directional sources, a point source in Room 1 with a parametric d_{op} was investigated, as shown in Figure 5c. Figure 9a and 9b present the average SPLs of each room with an omnidirectional point source in Room 1, i.e., source A. The results reveal that with increasing d_{op}, only the sound energy in Room 1 gradually decreased, whereas it increased in the successive rooms. Because the level of Room 1 was high, the magnitude of the change caused by the increase in d_{op} was not large, especially at low frequencies. Comparatively, the level of Room 5 was the lowest; therefore, the magnitude of the change was large. The closer the room was to the source, the smaller the change in level. Similar results were obtained with a directional point source in Room 1, i.e., source B as shown in Figure 10.

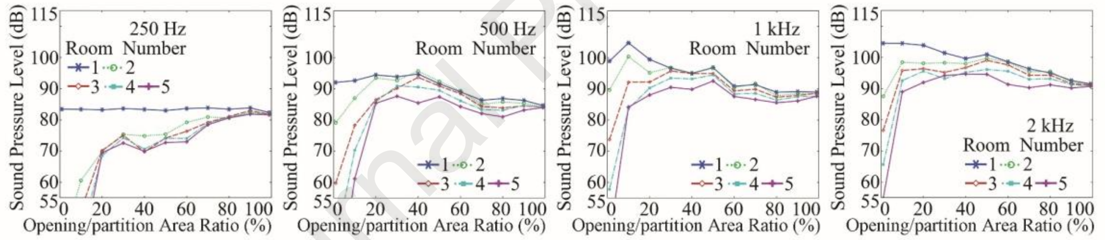


(a) *ab* = 0.01

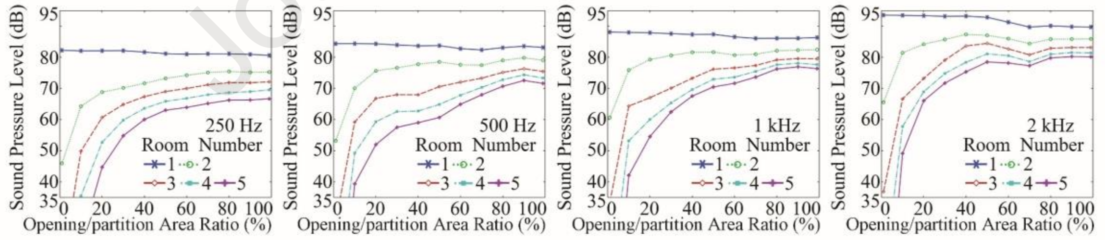


(b) *ab* = 0.5

Fig. 9. (Color online) Average SPL of each room for d_{op} from 0% to 100% with two *ab* with an omnidirectional point source in Room 1. (a) *ab* = 0.01 and (b) *ab* = 0.5.



(a) *ab* = 0.01



(b) *ab* = 0.5

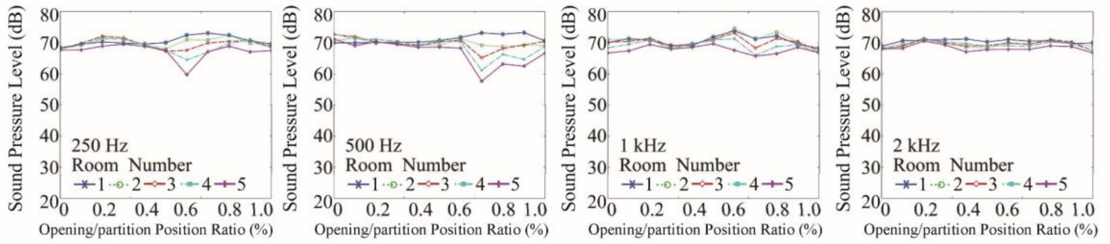
Fig. 10. (Color online) Average SPL of each room for d_{op} from 0% to 100% with two *ab* with a directional point source in Room 1. (a) *ab* = 0.01 and (b) *ab* = 0.5.

Therefore, in terms of the effect of an additional source (e.g., HVAC system and human speech) on a particular location or area, an additional source increased the level difference between rooms, indicating a larger change across the spaces. Only the average SPL of a room with an additional source exhibited a flat decrease rather than a sharp increase with increasing opening dimension, whereas those of other rooms increased indicating inconsistent behavior between the source and receiving rooms. In alleviating the effect of an additional source in the room, enlarging the opening dimension reduced the sound level for rooms with low absorption, but this effect could be very limited for those with high absorption.

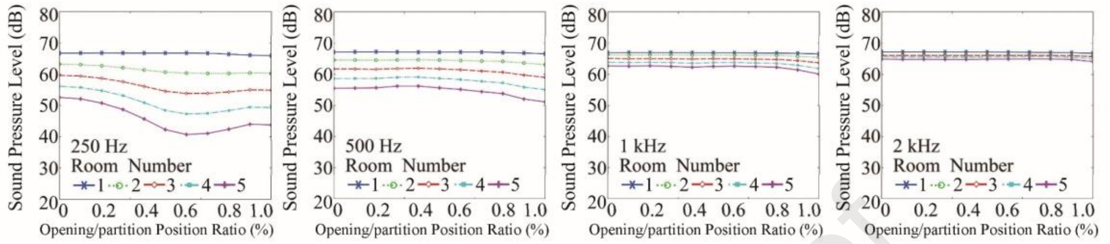
3.4. Effect of opening position

The opening position, which could be in the middle of the separating partition or against the side wall, clearly defines how people move across the spaces. It also divides the room volume into two functional parts. Figure 5d shows the experimental plan of the study. According to the definition of p_{op} discussed in Section 2, the larger p_{op}, the larger the distance from the opening to the middle of the separating partition. When the value of $p_{op} = (1-d_{op})/2\%$ is the maximum, it indicates that the opening is connected to the side wall.

Figure 11 shows the average SPL of each room for p_{op} from 0% to $(1-d_{op})/2\%$, for two values of ab. The results reveal that the sound field patterns for changing p_{op} at low and high room absorptions were essentially different. In the case of low absorption, as shown in Figure 10a, the levels changed randomly with increasing the p_{op}, i.e., from the opening being in the middle to the side; however, the attenuation according to the source–receiver distance can be observed. The range of the changing level in Room 1 was the smallest, and that for Room 5 was the largest. The level differences between the rooms were unrelated to p_{op}. In the case of high absorption, the levels in the rooms remain unchanged with increasing p_{op}, and the level difference between the rooms decreases with increasing frequency, as shown in Figure 11b. The reason for the opening position having a limited effect on the sound field for a high room absorption could be the lack of reflection, which is greater for a room with low absorption; therefore, in the case of low absorption, the sound field is significantly affected even for small changes in the opening position.



(a) *ab* = 0.01



(b) *ab* = 0.5

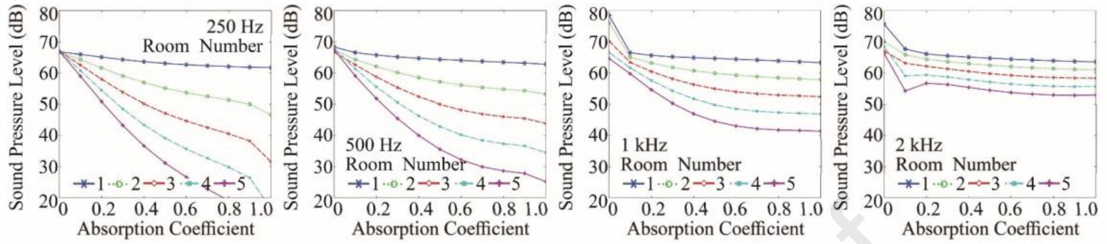
Fig. 11. (Color online) Average SPL of each room for p_{op} from 0% to $(1-d_{op})/2\%$ with two *ab* at $\theta = 0°$. (a) *ab* = 0.01 and (b) *ab* = 0.5.

Therefore, the influence of opening position on sound attenuation performance, i.e., whether the opening is located in the middle of the separating partition or against the side wall, could be observed only with a low absorption, which suggests a technique for professionals can utilize to determine paths for listeners. The average SPL of each room is kept at the same level irrespective of the opening position for a room with high absorption.

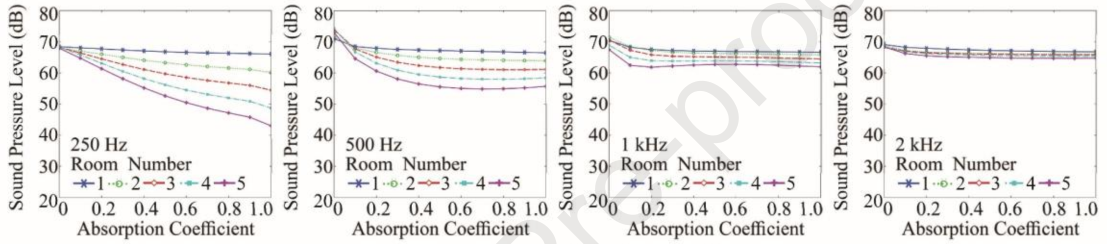
3.5. Effect of absorption coefficient

Adjusting absorption coefficient could be one of the most straightforward post-construction means of implementing noise control. To determine the effect of absorption coefficient on the distribution of absorption materials in the spaces, a study was conducted according to the experimental plan shown in Figure 5e.

Figure 12 shows the average SPL of each room for the parameter *ab* in the range of 0–1 with d_{op} = 20% and 40%. The results reveal that the patterns for a small and large opening dimension were consistent. Note that the levels in Rooms 2, 3, 4, and 5 for d_{op} = 40% were significantly lower than those for d_{op} = 20%, whereas the levels in Room 1 were equivalent for both d_{op} values. In general, the average SPL decreased within a certain range with increasing *ab*. The larger the source–receiver distance, the larger the magnitude of the level change. It is also observed that the rate of change was higher at smaller *ab* than that at larger values. Thus, increasing *ab* to modify sound attenuation could be more effective at smaller *ab* than at larger values. As expected, the level differences between rooms at d_{op} = 20%, i.e., for a smaller opening, were much larger at all frequencies than those at d_{op} = 40%. For both d_{op} values, the level differences between the rooms were equal, possibly because the geometric dimensions were the same, and the difference gradually decreased with increasing frequency.



(a) d_{op} = 20%



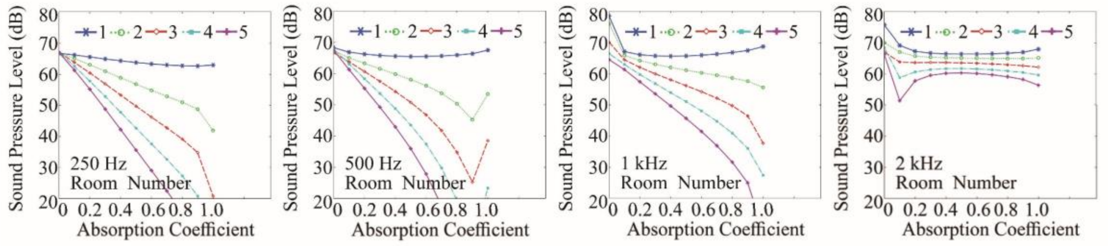
(b) d_{op} = 40%

Fig. 12. (Color online) Average SPL of each room for *ab* from 0 to1 with two d_{op} at $\theta = 0°$. (a) d_{op} = 20% and (b) d_{op} = 40%.

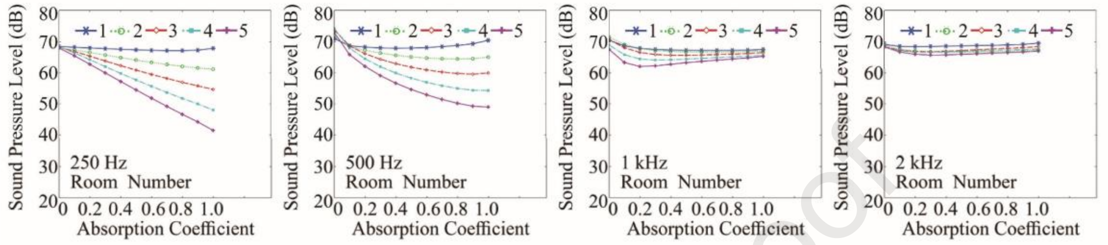
3.6. Effect of absorption position

Apart from changing the absorption coefficient, another simple approach is to adjust the absorption distribution. Figure 5f illustrates the experimental plan for this study to determine the effect of the absorption distribution. The absorption area was placed along the length of the sequential spaces, i.e., along the sound attenuation, while keeping the entire absorption amount equivalent to that of the plan shown in Figure 5e, i.e., the absorption was evenly distributed in each room.

Figure 13 shows the average SPL of each room for *ab* in the range of 0–1. The results showed that, under the assumption of equivalent absorption amount in each room, the difference in the levels when the absorption was positioned along the direction of the sound attenuation and when it was evenly distributed in the room was significant for smaller d_{op}, whereas it was negligible for larger d_{op}. It is observed that, for the smaller d_{op}, the levels decreased with increasing *ab* for the entire range of 0 – 1 rather than being within a certain range as shown in Figure 12a for evenly distributed absorption.



(a) $d_{\mathrm{op}} = 20\%$



(b) $d_{\mathrm{op}} = 40\%$

Fig. 13. (Color online) Average SPL of each room for *ab* from 0 to 1 with two d_{op} at $\theta = 0°$. (a) $d_{\mathrm{op}} = 20\%$ and (b) $d_{\mathrm{op}} = 40\%$.

3.7. Effect of number of rooms

The study was essentially aimed at large-scale spaces consisting of a number of small rooms. Figure 14 shows the average SPL of each room for *N* from 1 to 10 with two *ab* values and two θ values. The results reveal that with increasing *N*, the changes in the levels of the existing and added rooms differ according to the conditional room absorption. In the case of low absorption, as shown in Figure 14a, the level of the existing and added rooms was different for different *N*. However, the attenuation was similar irrespective of the number of rooms. In the case of high absorption, as shown in Figure 14b, not only the level values, but also the patterns remained the same for all frequencies, but the level range decreased with increasing frequency. It can be seen that by increasing the number of rooms, the level in Room 1 changed with low room absorption but remained constant for high room absorption.

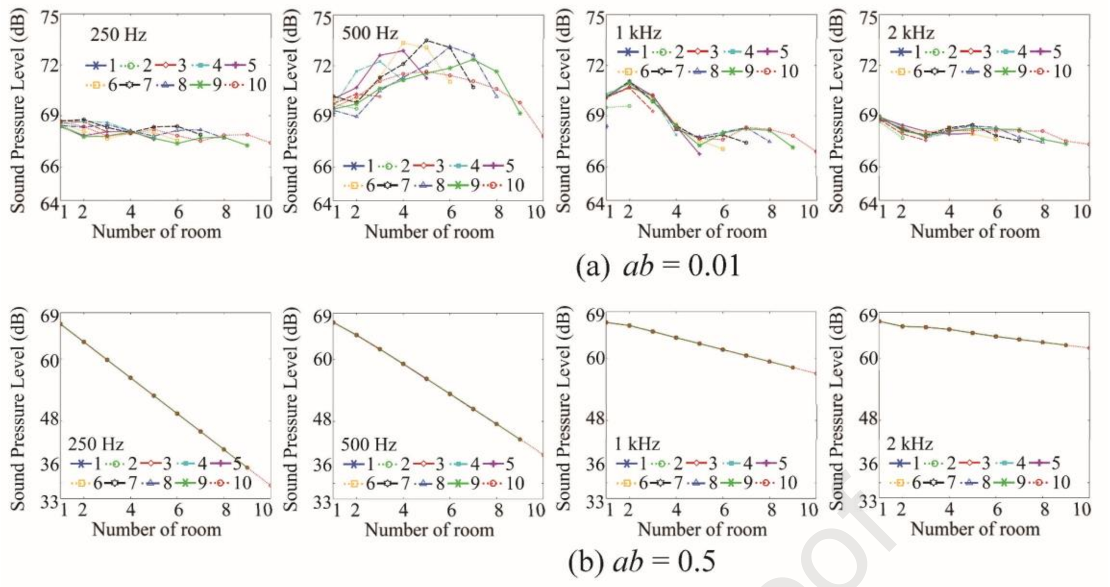


Fig. 14. (Color online) Average SPL of each room for *N* from 1 to 10 with two *ab*. (a) *ab* = 0.01 and (b) *ab* = 0.5.

4. Discussion

4.1. Limitations and future work

Although the FEM is relatively stable and effective for nature of energy-based advantage, the large amount of calculation confines this research to 2D modelling in the validity tests. Future work will involve more effective methods that could be enable 3D simulations to be conducted under high-frequency conditions so that issues such as the height of the spaces could be investigated. Moreover, there are other related aspects to consider in the future, e.g., rooms with circular and irregular shapes and rooms that are connected at the corner.

4.2. Designing choices under assumptions

As mentioned in Section 2, the schemes in which all parameters are modified are summarized in Table 1. Correspondingly, the results that should be used in the design phase by professionals are presented in Table 2.

Possible practical applications are presented in column of Application. Many previous studies have generally described how sound spreads and how it can be discouraged from spreading. The factor that should be considered for the sound path include the following: as the distance from the source increases, the received noise level slowly decreases; absorbent surfaces can help prevent sound travelling by reflections along corridors; and insulated walls help prevent sound transfer within buildings.

In this study, practical aspects of the results were determined under different assumptions, as shown in column of Assumption in Table 2. For most of the investigated schemes, such as the contextual factors, the assumptions of low/high room absorption, and small/large opening dimension, must be considered when applying the results. Normally, the larger the distance of the room from the source, the larger the magnitude of level change that could be obtained by the modification of parametric factors, as shown in the results of opening dimension results obtained in Studies 1, 2, and 3. Considering the just noticeable difference (JND) in the first receiving room, it is observed that most outcomes greatly exceeded the target JND, which is 0.25 dB at the most sensitive levels (greater than 60 dB) and frequencies (1–4 kHz) [35], except for the first receiving room with high absorption with an additional source. As an design objective in practice is often to achieve an ideal sound attenuation, Kang [35] noted that the absorbers used for as surface treatment must be evenly placed in long spaces. The results of Study 6 also demonstrated that an equivalent amount of absorption with a non-uniform or uniform distribution does not ensure consistent performance especially in the case of a small opening dimension. It is also worthwhile to note that according to McMullan [14] , increasing the sound absorption in a room has little effect on the sound passing between rooms. This finding was further confirmed in Study 5, where increasing the sound absorption in a room had little effect on the sound passing between rooms for rooms with high absorption, whereas the adjustments made to rooms with smaller absorption could result in greater changes.

Table 2. Results of each scheme showing the assumptions that should be considered, as well as the applications and guidelines that should be used by professionals in the design phase.

Scheme	Assumption	Main results	Application
Opening dimension	Room absorption: low/high	The average SPL of the room changes until the level difference between rooms stabilizes. It increases with increasing opening/partition area ratio for rooms with high absorption.	If a large opening is required, one should expect a high level in the room and small level difference between rooms for rooms with high absorption, while no such pattern is found for rooms with low absorption.
Dominant directional radiation of the opening	Room absorption: low/high	The level difference between rooms is larger for oblique incidence compared to horizontal one, particularly for rooms which are close to the source.	If the receiver is located at different height than the source, the level differences between rooms are larger than if the source and receiver are at the same height, and larger for rooms which are close to the source.
Directional radiation of the additional source	Room absorption: low/high	The average SPL of the room with an additional source remains or decreases with increasing opening/ partition area ratio by approximately 10 dB for rooms with high or low absorption, respectively. The level difference between rooms becomes larger with an additional source.	To reduce the level in the room with additional source (e.g., HVAC system and human speech), increasing the opening dimension could be useful, whereas the levels of other rooms increase with increasing opening dimension, especially for rooms with high absorption.
Opening position	Room absorption: low/high	The changes in opening position only affect the average SPL of a room with low absorption instead of high absorption.	To decide the path of the crowd across the spaces, consider opening position only for rooms with low absorption.
Absorption Coefficient	Opening dimension: small/large	Adjustments made within small absorption coefficients result in greater changes in the SPL than those made to high absorption coefficients.	The strategy of absorption adjustment as a remedial work yields limited benefits in the case of a room with high absorption.

Absorption position	Opening dimension: small/large	The difference in the SPL between applying uniform and non-uniform absorption distribution with a given absorption amount is larger with a smaller opening dimension.	The equivalent absorption amount between non-uniform and uniform distribution does not ensure consistent performance especially in the case of a small opening dimension.
Number of rooms	Room absorption: low/high	The level in the first receiving room remains constant for rooms with high absorption (e.g., with an absorption coefficient of 0.5). The difference between different absorption coefficients is about 6 dB maximum, depending on the number of rooms.	In case of increasing the entire scale of the space (e.g., number of rooms), to avoid interference in the first receiving room, high room absorption is necessary.

5. Conclusions

In this research, the predication accuracy of the sound attenuation in sequential rooms has been examined by validating the results of the FEM model with in-situ measurements taken in exhibition spaces. Then a parameter study has been carried out by considering contextual factors (opening dimension and position, number of rooms), acoustical factors (absorption coefficient and position) and source factors (directional radiation of the opening and additional source) in determining the effect on the SPL in the rooms. It has been found that:

- (i) In rooms with high absorption, the average SPL of the rooms is higher and the level difference between rooms is smaller with a larger opening dimension, whereas in rooms with low absorption the changes are more complicated. The opening position only has impact for rooms with low absorption.
- (ii) The level differences between rooms are larger for oblique radiation compared to horizontal radiation, especially for rooms which are close to the source. With an additional source (e.g., HVAC system and human speech) in a room, the level in this room is kept or reduced by approximately 10 dB with increasing opening dimension for rooms with high or low absorption, respectively, whereas the levels in other rooms increase for rooms with high absorption, but there is no clear tendency for rooms with low absorption, with increasing opening dimension.
- (iii) Generally speaking, the changes achieved by absorption are more significant under the conditions of low absorption. The difference in the average SPL between uniform and non-uniform absorption distribution with a given absorption amount is greater with a smaller opening dimension.
- (iv) The effects on the SPL in the first receiving room, caused by adding more sequential rooms, is less when the absorption in those rooms is high (e.g., with an absorption coefficient of 0.5), and the difference between different absorption coefficients is about 6 dB maximum, depending on the number of rooms.

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Highlights

- 2D modelling using finite element method is validated by in situ measurements.
- The parametrizations of contextual, acoustical and source factors are effective in modifying sound attenuation.
- Design strategies should first consider the condition of opening and room absorption.

Declaration of interests

☒ The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

☐The authors declare the following financial interests/personal relationships which may be considered as potential competing interests: