Investigation of the effective aperture area of sliding and hinged doors between coupled spaces

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Abstract: Acoustical coupling between architectural spaces can be implemented by sliding or hinged doors. This study compares the effects of these variable coupling area designs on the sound field using temporal energy decay curve analysis. Varying the aperture size alters the multi-slope decay curve properties such as the decay rate of each slope and their point of intersection (time and level). A predictive model is proposed, based on a geometrical approach and statistical theory for coupled volumes. Differences between scale model measurements and analytical predictions are quantified by means of deviations of acoustical parameters; reasonable agreement is found.

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1. Introduction
Coupled spaces can be encountered in various venues such as factories, large religious buildings with sub-volumes, theaters with stage houses, and concert halls with reverberation chambers. Acoustical coupling occurs through an open area which can be variable between rooms, inducing changes in sound field behavior within each volume. Several types of coupling area control constructions can be found with the most common being either a sliding door, providing a simple open area, or a hinged door, which can be described as an open area of wall combined with a moving reflector. The latter is the more common in actual coupled volume concert halls. This study concerns how the physical aperture opening varies relative to the effective acoustical coupling area when used to modify the acoustical room response. This aperture does not vary at the same rate depending on the type of coupling area, e.g., rotating or sliding. Therefore, comparing these coupling system designs provides insight regarding means of sound field control in rooms. It should be noted separately that apart from the coupled response, the use of hinged or rotating doors can also drastically change the early reflection pattern, which is not the case for sliding doors. This aspect of the door effect is not considered in the current study.

Previous research has studied coupling area variation. Typically, a simple open area is employed, i.e., a sliding door. Early acoustical research compared measurements to analytical models using statistical acoustics in large coupled rooms, including coupling area variation. Later works used computer simulations such as ray-tracing to study large coupled volume concert hall acoustics. Other studies focused on smaller coupled volumes, involving modal acoustic behavior, and the effect of the size of coupling area. Another study used a 3D-model of rotating doors for ray-tracing software in coupled volume concert halls. In this case, as mentioned earlier, the door plays the role of sound reflector, sending acoustic energy to the

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reverberation chamber or to the main room depending on the incident sound direction and door orientation. This coupling configuration is more complex than a simple open area and is more realistic regarding actual coupled volume concert halls. Recent studies have also examined the ability of different numerical methods to model coupled volume acoustics.\textsuperscript{11,12}

The present study first intends to quantify the differences observed between coupling system designs comparing sliding and hinged or rotating doors. Recorded impulse responses using a scale model are analyzed and acoustical parameter variations are compared, providing an equivalent aperture in terms of open angle for the rotating door as compared to the aperture area as a function of open width for the sliding door. Subsequently, an analytical model is proposed, which allows for expressing the rotating door angle in terms of equivalent sliding coupling area. This model is based on geometric assumptions. Combined with a statistical theory describing coupled volume acoustics,\textsuperscript{13} this model can provide reasonable and rapid estimation of relevant acoustical parameters.\textsuperscript{12,14}

2. Scale model measurements

Measurements were performed in a 1:20 coupled room scale model. A schematic of the scale model and measurement configuration can be seen in Fig. 1(A). A single source and receiver position were considered in the current study. Opposing walls were designed to be non-parallel (splay angle of 2°) in order to avoid flutter echoes. Reverberation times in the independent rooms transposed to full-scale are presented in Table 1. A schematic of the two door types under study are presented in Fig. 1(B) with their associated control variable: The width $w$ of aperture for the sliding door and the angle $\gamma$ of aperture for the rotating door. One of each of these doors was alternatively installed in the center of the partition wall for the scale model measurements.

Various analysis methods and quantifiers have been proposed in previous research on coupled spaces, namely, ratios of early and late decay times used to quantify the degree of curvature of sound energy decays, or individual decay time of each slope and their initial level estimated by a model-based method.\textsuperscript{15} Acoustical parameters were obtained in the present study from analysis of the measured impulse responses using the Marching Line analysis method.\textsuperscript{12,14} The decay curve quantifiers are the decay time ($DT_i$) of each slope within the curved decay, evaluated over 60 dB, and the time and level ($BP_{ti}$ and $BPL_i$) of the point on the decay curve between consecutive slopes, called the bending point, as illustrated in Fig. 2(A). This method is based on a recursive algorithm which calculates root-mean-square (rms) deviations between stepwise linear regressions the decay curve (represented by either the smoothed energy-time envelope or the Schroeder backward integration curve\textsuperscript{16}) of the impulse response (in decibels) to detect straight portions of the energy decay curve and estimate the relevant acoustical parameters. The two approaches provide slightly different results, but for comparisons between conditions, either method can be selected and used. The current study employs the Schroeder backward integration curve. In this study, with

Fig. 1. (A) Floor plan of the scale model. (B) Detail plan of the coupling area door types. $w$ is the aperture opening width of the sliding door and $\gamma$ is the aperture opening angle of the hinged rotating door. (C) Geometrical parameters of the rotating door and its projection on the separating wall defining the equivalent area between sliding and rotating doors.
the scale model composed of two rooms with high diffusion, the obtained energy decay curves present two slopes. While varying the coupling area globally alters the energy decay curves and the four coupled acoustical parameters ($DT_1$, $DT_2$, $BP_t$, $BP_L$), decay times are predominantly determined by the acoustic volumes and the absorption conditions, and the bending point level and temporal position is primarily affected by the coupling area (see Luizard et al., Figs. 8 and 9). To avoid redundant information and retain the most consistent acoustical parameter, only $BP_L$ is presented here to quantify the effect of coupling area variation on the resulting sound field in the main room.

Figure 2(B) shows the bending point level ($BP_L$) at the receiver position, in four octave bands from 125 Hz to 1 kHz, for the two door types. Considering the case of 125 Hz octave band [i.e., the two curves on the right side of Fig. 2(B), with higher values of $BP_L$], the curve corresponding to the sliding door is relatively linear, while the curve corresponding to the rotating door presents a rapid variation for small opening angles and less variations for larger opening angles. This trend is observable in each considered octave band. In addition, $BP_L$ values corresponding to the 500 Hz centered octave band are slightly higher than those observed at 250 Hz octave band, on the order of 1 dB on average (see Table 2), which does not follow the progression of reverberation times (Table 1). This fact could be due to the similarity of the reverberation times in the scale model’s main room in the 250 Hz and 500 Hz octave bands, inducing similar $BP_L$ values. Furthermore, the measurement and analysis process leads to a range of uncertainty of $BP_L$ of ±1.5 dB as can be seen in Fig. 2(B), where the values in the rotating door case at 250 Hz would be expected to be practically constant for $\gamma > 100^\circ$, as compared to other frequency bands.

3. Predictive model

A geometrical approximation model of equivalent effective area is proposed for rotating doors. This model is based on the projection of an open rotating door on the wall separating the main room and the reverberation chamber, as presented in Fig. 1(C). This equivalent area is composed of two triangles at the top and bottom of the door and a rectangle between the end of the door and the wall. Eq. (1) presents the relation

![Figure 2](image-url)
of parameters illustrated in Fig. 1(C) to obtain the equivalent area $A_{eq}$ between sliding and rotating doors.

$$A_1 = A_2 = \frac{1}{2}L \sin \gamma; \quad A_3 = 2HL \sin \frac{\gamma}{2}; \quad A_{eq} = A_1 + A_2 + A_3.$$  \hfill (1)

This expression can be compared to the open area in the case of a sliding door, which is a function of the open width $w$ such that $A_s = wH$, $H$ being the fixed height of the rectangular door. Figure 3(A) shows the proposed open area calculation for each type of door as a function of the opening width $w$ and the opening angle $\gamma$. This area increases linearly for the sliding door while it increases faster for the rotating door as a function of angular opening until a threshold at $\gamma \approx 90^\circ$, where the largest coupling area is reached.

This model is evaluated by using these areas as input parameters to a theoretical model of sound energy decay in coupled spaces, including the geometrical and acoustical specificities of the scale model (Table 1). This theoretical model considers a closed system of ideal (Sabinian) reverberant volumes exchanging sound energy. An acoustical power balance considering these cavities successively leads to a system of differential equations whose solution in the transient excitation condition is a linear combination of exponentials with decay rates $\delta_i$ and initial energy levels $E_{ij}$. These quantities can be related to the previously mentioned quantifiers $DT_i$ and $BP_{LT}$, respectively, allowing comparisons between the models of aperture and the analyzed scale model measurements. The obtained sound energy decay curves provide various bending point levels ($BP_L$) depending on the considered coupling areas. Figure 3(B)

![Fig. 3. (Color online) Predictive model. (A) Geometrical approximation model of equivalent opening for sliding and rotating doors. (B) Results from the statistical theory in terms of bending point level in which the model of opening (A) is used as an input parameter.](image-url)
presents the $BPL$ values obtained for the sliding and rotating doors. The range of coupling areas represents areas from 0.08% to 0.5% of the total surface of the main room. The trend of variation is similar to Fig. 3(A).

4. Results

4.1. Comparison between measurements and theoretical model

Results from the theoretical model are compared to those from the scale model measurements. The trends of variation observed in Fig. 2(B) and Fig. 3(B) appear to be globally similar with quasi-linear variations in the sliding door cases and curved variations in the rotating door cases. As the doors are wide open, $BPL$ values from theory and measurements are comparable, with an average difference of 1.5 dB. For the smallest apertures, inferior to 0.1% of the total surface of the main room, results are similar for the rotating door, but discrepancies with the theory appear for the sliding door with $BPL$ being about 10 dB lower than measurements. A quantified comparison is presented in Table 2 and Fig. 4, where mean $BPL$ values are given for sliding and rotating doors between measurements and theory in octave bands.

The sliding condition shows good agreement for all but the smallest opening. Differences between measurements and theory are within ±5 dB. There is some slight overestimation or underestimation for different octave bands, with an overall mean difference of $-0.8 \pm 3.5$ dB. This difference reduces to $0.7 \pm 1.2$ dB if the smallest opening is no longer considered. The rotating condition shows good general agreement across opening angles with less variance between frequencies but a general positive bias error, resulting in an overall mean difference of $1.9 \pm 1.3$ dB. In general, the results show good agreement, with the principal deviations occurring at the 250 Hz octave band.

4.2. Discussion

As $BPL$ tends to increase with coupling area, the proposed model of equivalent rotating aperture slightly overestimates coupling area, leading to overestimated $BPL$ values. However, the general deviance of the model falls within the observed variations of the sliding aperture results, which correspond to the differences between the idealized statistical theory and the actual physically measured room and are not a direct function of the aperture model.

An alternate theoretical effective area model could consider the three surfaces (two triangles and one rectangle) limited by the rotating door edges and the open part of the separating wall, as opposed to the door projection on the opening [Fig. 1(C)] as was employed here. The total surface calculated by this model would be larger than that of the proposed model and would therefore further increase the current overestimation.

5. Conclusion

This study proposes a geometrical approximation model of equivalent area between sliding and hinged/rotating doors. Comparisons of this model in conjunction with a
statistical model of sound energy decay in coupled volumes and scale model measurements have shown good agreement. An acoustical parameter adapted to multi-slope energy decay, namely, the bending point level ($BPL$) was used to quantify the comparisons. Results show that average deviations lie within a few dB for each type of door, within the expected measurement variance. In the context of a coupled volume concert hall, the various types of doors (sliding and rotating) presented in this study offer different manners to tune a coupled room response, for a final equivalent result. Sliding doors present a linear effect relative to opening area adjustments on the acoustics of the venue while rotating doors present greater variations for changes in small opening angles and smaller variations in relation to changes in large opening angles, allowing for rapid alterations in the response but requiring more precise handling of door apertures.

Recent perceptual studies have attempted to establish the perceptual sensitivity of variations in coupled decay responses relative to decay rates and coupling area. The later of these studies identified a perceptual threshold of 10% change in coupling area. Such information can be used in conjunction with the proposed model of equivalent area between sliding and hinged doors in the context of coupled volume architectural design in that the ease and flexibility of adjusting the acoustics of the hall can be optimized around a desired acoustic coupling effect. As such, these findings are expected to be useful to room acoustics researchers as well as actual concert hall designers and managers. Further studies are necessary to extend preliminary perceptual studies with regards to perceptual preferences of coupled decays for different music genres.

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References and links