doi:10.1016/j.apacoust.2021.108465

Effects of the absorber location on low-frequency noise control in typical dwelling layouts

Yang Song[a,1,*], Jian Kang[b,2,*]

[a]School of Architecture, Harbin Institute of Technology; Key Laboratory of Cold Region Urban and Rural Human Settlement Environment Science and Technology, Ministry of Industry and Information Technology, 92 West Dazhi Street, Harbin, China
[b]UCL Institute for Environmental Design and Engineering, University College London (UCL), London WC1H 0NN, London, United Kingdom
[1]ORCID iD: https://orcid.org/0000-0003-0188-5843
[2]ORCID iD: https://orcid.org/0000-0001-8995-5636

***** Corresponding author

Abstract[1]: Studies on the effects of absorber location on low-frequency noise control in acoustically coupled rooms have been limited. This study investigated the effects of the absorption area and location on low-frequency noise control in typical dwelling layouts for different room connection types. In-situ measurements under a steady-state noise showed significant results in rooms with an absorber. An absorption area of only 5–6 m^2 in the bedroom, wherein noise enters first, was equivalent to an area of 22.5 m^2 in the bedroom farthest from the sound source. Noise reduction generally increased by 0.3–0.5 dB/m2 within 7.5 m^2 absorption area, and later increased by less than 0.2 dB/m^2 or became overdamped. Moreover, the standard deviation of the sound pressure level (loud–quiet difference) increased with the absorption area in the living room, while it decreased in the bedroom oriented to the sound source. Noise reduction was constantly high (approximately 6–7 dB) when the absorption area distribution proportion between the living room and the bedroom oriented to the sound source was within 1:5–5:1. Further, the optimal and worst absorber locations were also suggested to ensure a low-frequency noise control in the layouts.

Keywords: dwelling, low-frequency noise, absorber location, noise reduction, layout

2022 Applied Acoustics
Date Received: 14 May 2021 **Date Accepted**: 7 October 2021
Available online: 29 October 2021

[1]***Abbreviations***: RL, room level; ASA, asymmetrically structured absorber; SPL, sound pressure level; STD, standard deviation

doi:10.1016/j.apacoust.2021.108465

1. Introduction

Low-frequency noise has pervasive sources in residential areas [1-3], causing health risks [4-6] and more annoyance than high frequency noise [7-10]. The existing techniques for noise reduction can better attenuate high-frequency noise than low-frequency noise [11-12], due to the less attenuation distance and outdoor to indoor noise reduction at low frequency [13]. Protrusive devices on dwelling facades, such as lintels and balconies, are not effective for low-frequency noise control [14]. The connections between rooms, on the other hand, could significantly affect the low-frequency noise control as access to a quiet side of a dwelling reduces the self-reported annoyance by up to 30%–50% when the sound pressure level difference between the most and least exposed facade is not less than 10 dB [15-17]. Tang et al. indicated that the arrangement of partition walls affects the surface absorption of rooms and the noise attenuation of windows [18]. This theory was supported by Song and Kang, who inferred that a 'parallel connection' between rooms might ensure a higher low-frequency attenuation [19]. Therefore, the required safe distance could be reduced, thus, saving land resources. Noise reduction and loud-quiet difference (standard deviation of the sound pressure level) should be considered to indicate the absorber performance in a dwelling layouts.

Limited studies have been conducted on the effect of the absorber location on the noise reduction in dwellings; moreover, most studies are mainly focused on the reverberation time. Studies on the low-frequency range are rather limited. Studies on the low-frequency sound field in rooms started in the 1940s with research by Bolt, who suggested appropriate room geometry and dimensions to achieve a smooth response [20]. Morse formulated the basic theory of low-frequency sound transmission and vibration [21]. Russ and Meissner studied the influence of the boundary conditions in rooms with an irregular and fractal shape based on the wave theory [22,23]. It was observed that the absorber location influenced the reverberation time at low frequencies, which was mainly affected by the absorber located on the lateral walls. When the absorber was located on the floor or the ceiling, the reverberation time was scarcely affected [24]. This was supported by Eda's study, which showed that partial elements positively affect the frequency response in rectangular rooms [25]. The presence of elements, such as furniture, was proved to ensure a shorter reverberation time and lower sound pressure level in single-bed hospital wards [26]. The absorber location was also proved to influence the listening area of a dwelling room [27]. Existing studies have mostly been conducted on the eigenmode, flatness of the frequency response, and uniformity of the sound level distribution. Conversely, there remains a lack of research on noise control at low frequencies.

In-situ measurements to investigate the effects of the absorber location on the low-frequency noise reduction in dwelling layouts are necessary. In fact, the validity of the theoretical formulas and simulation methods under complex room coupling conditions at low frequencies remains to be demonstrated. Okuzono developed a finite-element formulation to predict the sound field and a frequency-domain finite-element method to analyse the absorption characteristics in a single room [28-30]. For two adjacent rooms, the sound insulation of the partition wall was found to depend on the modal characteristics of each part of the room–wall–room system through finite-element analysis [31]. However, the room connections in practical dwelling layouts are much more complicated than those between one or two rooms. Another relevant work is acoustics in long enclosures, although the sound transmission between different rooms was not considered [32,33]. Limited studies on sound transmission in sequential spaces paid less attention on low frequencies [34]. Research on multi-room sound transmission at low frequency is needed.

The aim of this research was to investigate the noise reduction for different room connection

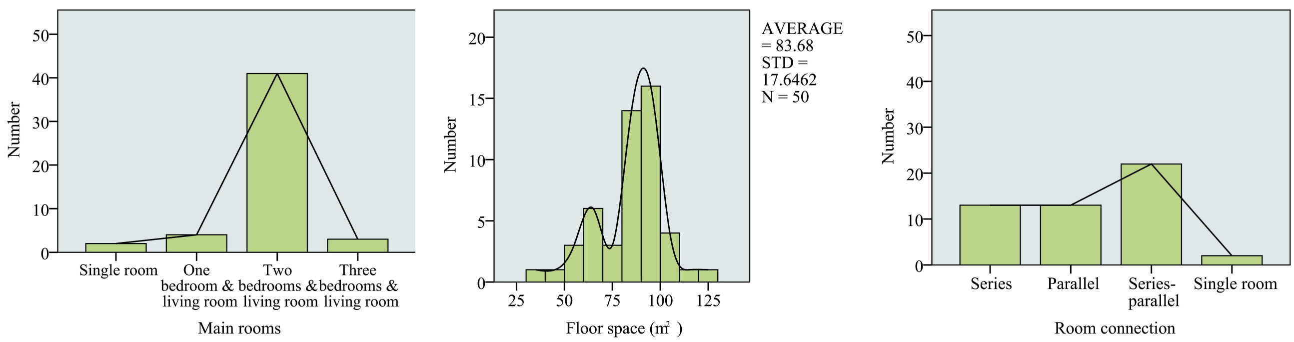
doi:10.1016/j.apacoust.2021.108465

types of dwelling layouts with different absorption levels and location, and suggest the optimal cases, considering the lack of studies on the performance of the low-frequency sound absorption in multi-room systems. In-situ measurement of 'series', 'parallel', and 'series-parallel' room connections were carried out [19]. The effects of the rooms with absorber, absorption area, and absorption area distribution proportion between two rooms on the absorber noise reduction and the standard deviation of the sound pressure level in dwelling layouts were investigated at low frequencies. In addition, the best and worst absorber locations have been proposed in this paper, providing suggestions and guidance for low-frequency noise control in dwellings.

2. Methodology

Layout classification

Analogous to the relations between the electric circuit elements, room connections are defined as series, parallel, and series-parallel [19]. One hundred twenty-three typical layouts of modern Chinese dwellings were summarised as the population; among them, 50 layouts were selected by simple random sampling with replacement [35,36]. If the selected layout had multiple possible source orientations, the orientation was determined through a random number generated by rolling a dice. Figure 1 shows the scales and room connections of the 50 sample layouts. In terms of scale, there could be 1–3 bedrooms and a living room as the main rooms of the layout. Two-bedroom layouts are the most typical (82%). A standard floor covered approximately 90 m^2, and this was consistent with Zhou's results on the dwelling layout development [36]. The series-parallel connection is the most common room connection, followed by the series connection and parallel connection. As the frequencies of these three types of room connections are significant, they should be included during the test site selection.



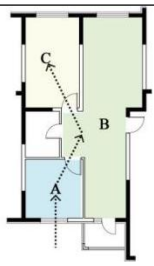
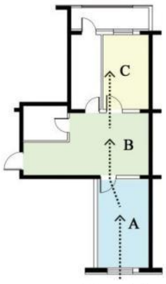
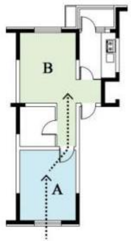
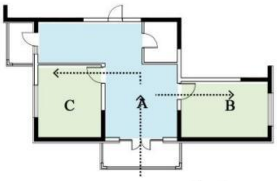
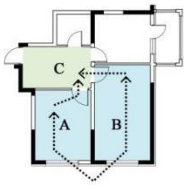
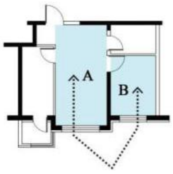
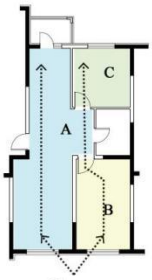
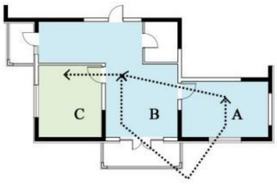
(a) Main rooms (b) Floor space (c) Room connection

Fig. 1. Scale and room connection distributions of the dwelling layouts

Series, parallel, and series-parallel room connections were classified to propose the most common layout types. Table 1 lists the room connection types and corresponding subdivision types. A two-bedroom layout, with a living room having windows, typical in standard units of slab-type dwellings, was the most common series-connection layout. In this layout, the sound sequentially entered one of the two bedrooms, the living room, and the other bedroom. A three-orientation layout, commonly found in end units, was the most common parallel-connection layout. The sound entered the living room first, and later, entered the two parallel-connected bedrooms in this layout. A blend-arranged layout was the most typical and the most representative series-parallel-connection layout among all the tested layouts. This layout type was commonly seen in standard units of slab-type dwellings, and sound propagated through one of the bedrooms and the living room before entering the other bedroom.

doi:10.1016/j.apacoust.2021.108465

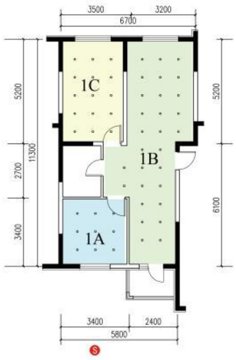
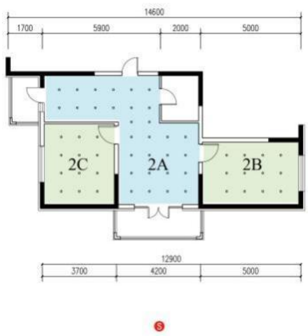
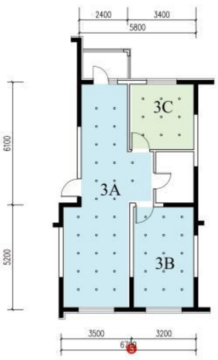
Table 1. Classification of typical series, parallel, and series-parallel layouts. The tested areas are: the first room level in blue, second in green, and third in yellow.

Room connection	Subdivision types	Layout plan	Frequency of occurrence	Typicality
Series connection	Two-bedroom layout with a living room with windows		7/13	√
	Two-bedroom layout with a living room without windows		3/13	
	One-bedroom layout		3/13	
Parallel connection	Three-orientation layout		9/13	√
	Corner layout		2/13	
	Single-orientation layout		2/13	
Series-parallel connection	Blend-arranged layout		20/22	√
	Transverse-arranged layout		2/22	

Tested layouts

This research investigated the three most typical layouts of the series, parallel and series-parallel connections, as mentioned in the layout classification in Section 2.1. The tested layouts had the same floor dimensions (90 m^2) and two bedrooms to ensure their comparability and typicality. The volume of most typical rooms was between 20 and 200 m^3. According to Schroeder, when the desired frequency range is 100–200 Hz (further discussed in Section 2.5) and room reverberation time is approximately 0.5 s, the rooms below 200 m^3 can be considered as acoustically 'small' rooms [37]. Sound field in such rooms cannot be simplified as diffuse. The 100–200 Hz range includes the band below the Schroeder cut-off frequency and contains adequate mode counts, and hence, it is considerably influenced by axial, tangential, and oblique modes. The volumes of the living room, master bedroom, and guest bedroom were approximately 90 m^3, 50 m^3, and 30 m^3, respectively, which are standard dimensions below 200 m^3. The subsequent results will thus, be applicable to layouts, with volumes of single rooms ranging from 20 to 200 m^3.
Table 2 lists the distances and paths of the sound transmission and the dimensions and space arrangements of the tested layouts. L1, L2, and L3 represent the three layouts that include the series, parallel, and series-parallel room connections, respectively. The three main rooms are series-connected in L1, two bedrooms are parallel-connected in L2, and the three main rooms are series-parallel-connected in L3. L2 and L3 are two different layouts as they have different source orientations, room connections, and sound propagation paths.

Table 2.
Types and characteristics of the tested layouts. The tested areas are: the first room level in blue, second in green, and third in yellow.

Layout		L1	L2	L3
Plan with source and receiver positions (the red dot at the bottom of the diagrams represents the source)				
Sound transmission distance	Max. polyline distance (m)	12.2	10.4	12.3
	Max. Linear distance (m)	12.2	9.8	11.3
	Depth (m)	11.3	8.1	11.3
Sound transmits through	Room levels	3	2	2
	Number of doors in living room	4	4	4
	Concrete wall length proportion (%)	17.9	17.2	17.9
Dimension and space arrangement	Room connection	Series connection	Parallel connection	Series-parallel connection
	Geometrical arrangement	Blend	Transverse	Blend
	Number of bedrooms	2	2	2
	Floor space (m^2)	90	90	90

Absorber location

An asymmetrically structured absorber (ASA), a sound-absorbing cotton sheet with an adequate acoustic absorption at low frequency, was used in this study as a sound absorber. Figure 2 shows the absorption coefficients for each frequency band. The absorption coefficients were measured based on ISO 354:2003 in a reverberation room, where the sound absorber was mounted on a frame [38]. Moreover, ISO 266:1997 was also used as reference for preferred frequencies [39]. The absorption coefficients were higher than 1.0 as the samples were backed by a 200 mm air gap rather than being directly mounted on the sidewall. This setup allowed an effective absorption area higher than the projected area. The measurement procedure was in accordance with the absorption coefficient measurements. To make the location of absorber on each surface independent, it was placed uniformly on each sidewall and the ceiling; moreover, the absorption area was increased symmetrically with respect to the centre of each surface. The absorbers were arranged on the ceilings and sidewalls because acoustic treatments on these boundaries are strongly related to the distribution of absorption in a given layout [40].

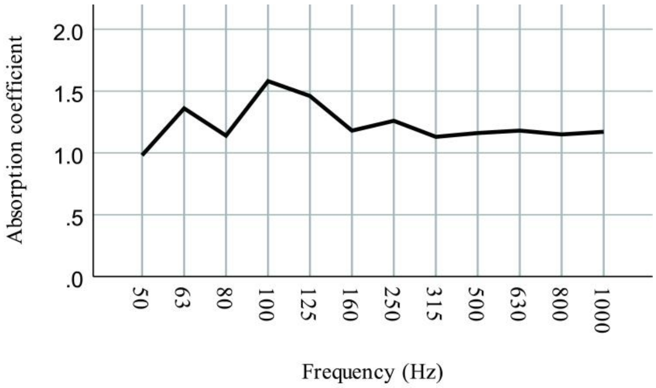


Fig. 2. Absorption coefficient of the asymmetrically structured absorber (ASA) at different frequencies

When the sidewall and ceiling, except the door-opening and windows, were fully covered by the ASA, the total absorption area was 22.5 m^2, which is the maximum absorption area reached in this study. To investigate the effect of the rooms with the absorber, the absorber was placed in one or two main rooms, and the total absorption area was 22.5 m^2. In one room, the absorption area was increased from 0 to 22.5 m^2 at intervals of 3.75 m^2 to investigate its effects. The absorption area distribution proportion is defined as the proportion between the absorption areas in two rooms, and it ranged from 0:6 to 6:0. The absorber (total absorption area of 22.5 m^2) was transferred at intervals of 3.75 m^2 from one room to another to investigate its effect. Table 3 lists in detail the absorber locations.

Table 3.
Absorber location conditions in the tested layouts

Factors Absorption area (m^2) Room	Series connection			Parallel connection			Series-parallel connection		
	1A	1B	1C	2A	2B	2C	3A	3B	3C
Room with absorber	22.5	0	0	0	22.5	0	22.5	0	0
	0	22.5	0	0	0	22.5	0	22.5	0
	0	0	22.5	0	11.25	11.25	0	0	22.5
	7.5	7.5	7.5	0	0	0	7.5	7.5	7.5
Absorption area	0,3.75,7.5,...,22.5	0	0	0	0,3.75,7.5,...,22.5	0	0,3.75,7.5,...,22.5	0	0
	0	0,3.75,7.5,...,22.5	0	0	0	0	0	0,3.75,7.5,...,22.5	0
Absorption area distribution	0	22.5	0	0	0	22.5	0	22.5	0
	3.75	18.75	0	0	3.75	18.75	3.75	18.75	0
	7.5	15	0	0	7.5	15	7.5	15	0
	11.25	11.25	0	0	11.25	11.25	11.25	11.25	0
	15	7.5	0	0	15	7.5	15	7.5	0
	18.75	3.75	0	0	18.75	3.75	18.75	3.75	0
	22.5	0	0	0	22.5	0	22.5	0	0

Measurement procedure

The fixed microphone positions and numbers during the designing measurement procedure were determined based on ISO 10140-4:2010 and adjusted [41]. The windows oriented toward the sound source remained open while the others were closed. If the entrance door was closed and no interior doors were installed, the test condition could represent the noisiest state of tested layouts under environmental noise. This configuration would also avoid the results being affected by the state (open–closed) of the interior doors, their opening angle, and room modes (resonances of three-dimensional wobbling air in a room). An omnidirectional spherical sound source was placed outside the window of the main room of the tested layouts, approximately 7 m away from the centre of the layout facade at a height of 1.85 m. The receiver positions in a 0.9 m × 0.9 m grid at a distance of 1.5 m from the floor were measured under a steady-state pink noise (Table 2), referring to ISO 29955, to study the sound pressure level (SPL) in the layouts [40]. The level of the sound source decreased by 3 dB per doubling of the band centre frequency [42]. The distances between the receiver positions and sidewalls were no less than 0.3 m. Moreover, a reference position at 1 m from the centre of the open windows was added inside each layout. As a result, possible sound level differences can be detected around the windows due to variation in the exterior wall insulation and outdoor landscape.

Data calculation and evaluation of noise control

The measured data were analysed according to ISO 10140–4:2010 procedure of correction and spatial averaging [41]. Only the main rooms, namely the bedrooms and living rooms, were assessed, whereas the toilets and kitchens were considered as noisy rooms. This study focused on the frequency range of 100–200 Hz as the measurement methods differ for frequencies above and below 100 Hz, and the frequency band of the traffic noise is usually down to 100 Hz. The one-third octave band at 800 Hz was used as a corresponding group at higher frequencies.

To evaluate the noise control of the absorber, two indices, namely the noise reduction and loud-quiet difference, were analysed. In this study, noise reduction is defined as the average

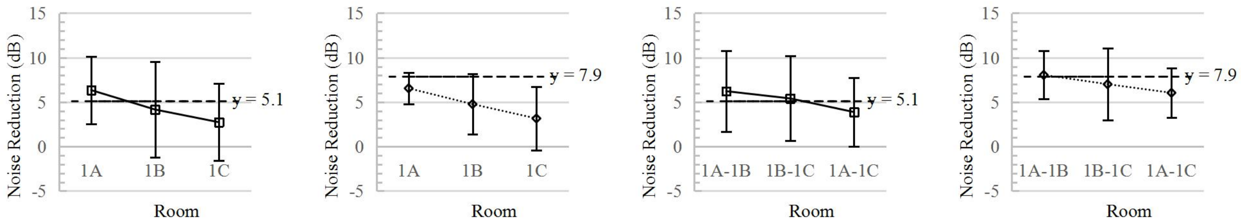
doi:10.1016/j.apacoust.2021.108465

SPL difference of the receiver positions before and after using the acoustic absorber. This index describes the overall attenuation caused by the absorber. Conversely, the loud-quiet difference is defined as the standard deviation (STD) of the SPL values at the tested receiver positions. The STD rather than the range of SPL is selected because significant spatial variation in the SPL is a main feature of the modal sound field. Consequently, the maximum and minimum low-frequency noise levels in dwelling layouts are likely caused by accidental phase coincidences [43]. Therefore, the STD is considered as a more representative index of the loud-quiet difference to describe SPL distribution in a layout. According to the results of previous studies, a higher loud-quiet difference may assist in producing quiet sections in layouts, thereby reducing annoyance [44] [15-16]. These indices along with the room connection types could better indicate the noise control of the absorber.

3. Results

Effects of rooms with an absorber

When more than one room had an absorber in the tested layouts, the low-frequency noise control performance did not improve. Figure 3 shows the noise reduction when the absorber was present in different rooms in a typical series-connection layout, and the loud-quiet difference is shown in error bars of ±1/2 standard deviation of the SPL. The noise reduction obtained with a 6.25 m^2 absorber in the RL1 room was equivalent to that obtained when an absorber of 20 m^2 or 22.5 m^2 in the RL2 or RL3 rooms, respectively. Furthermore, placing the absorber in RL1 and RL2 simultaneously could ensure the best low-frequency noise control in terms of noise reduction and loud-quiet difference (6.2 dB and 10.8 dB, respectively). When only one room had an absorber, the average noise reduction decreased from 6.3 dB to 3.2 dB as the room level increases. If the absorber was only in RL1, the noise reduction was higher than that obtained from the average distributed location in three rooms (Figure 3a). However, the loud-quiet difference of this absorber location was the lowest (only 7.6 dB), whereas that of the absorber in RL2 was considerably higher (10.8 dB). When the absorber was placed in two rooms simultaneously, the noise reduction shows a peak when the absorber was in RL1 and RL2 (room 1A and 1B), as shown in Figure 3c. The lowest noise reduction occurred when the absorber was placed in RL1 RL3 (less than 4 dB). As for the noise reduction, the loud-quiet difference was low when the absorber was placed in RL1 RL3 (7.7 dB), whereas it was slightly high when the absorber was in RL1 RL2 or RL2 RL3 (more than 9 dB). This may be related to the normal mode theory for non-diffuse field. According to Hopkins, axial modes play an important role in sound decay when one dimension of the room is considerably longer than the other two [42]. The proportion of the length to width and height of the living room was approximately 2:1:1. The absorber may sufficiently attenuate the energy of axial modes, and consequently form a quiet section at the end far from the sound source in the living room rather than in Room 1C. The count of axial modes reduced with frequency and its effect significantly decreased when the room dimensions were significantly more than the wave length [42]. Hence, the results may only be applicable to acoustically small rooms at low-frequency and not to large-scale hall spaces. At 800 Hz, the noise reduction in the layout increased with the number of rooms having the absorber. This result was inconsistent with those obtained in a low-frequency band.



(a) Absorber in one room, 100–200 Hz
(b) Absorber in one room, 800 Hz
(c) Absorber in two rooms, 100–200 Hz
(d) Absorber in two rooms, 800 Hz

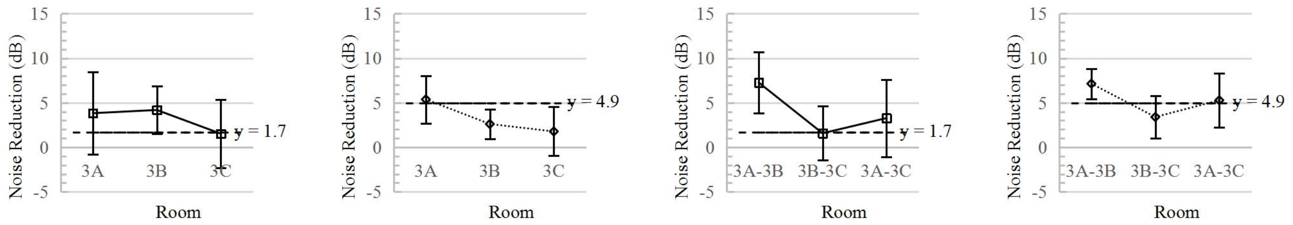
Fig. 3. Noise reduction obtained by placing the absorber in different rooms in a typical series-connected layout (line: noise reduction; error bar: ±1/2 loud–quiet difference; horizontal reference line: noise reduction obtained from the average distributed location in three rooms) at typical frequencies of 100–200 Hz and 800 Hz.

In a typical parallel-connection layout, the values of the noise reduction obtained by placing the absorber in one or two parallel-connected rooms were similar (approximately 3 dB), whereas the loud-quiet difference showed considerable variations. The calculated noise reduction and loud-quiet differences are shown in Figure 4. The loud-quiet difference was higher when the absorber was in Room 2B (8.9 dB), and the value was 2.5 dB lower when the absorber was in Room 2C. On the contrary, the loud-quiet difference did not significantly vary at 800 Hz with different rooms with the absorber, whereas the noise reduction varied by 1.5 dB.

(a) Absorber in one room, 100–200 Hz
(b) Absorber in one room, 800 Hz

Fig. 4. Noise reduction when the absorber is in different rooms in a typical parallel-connected layout (line: noise reduction; error bar: ±1/2 loud–quiet difference; horizontal reference line: noise reduction obtained from the average distributed location in two rooms) at the typical frequencies of 100–200 Hz and 800 Hz.

In a typical series-parallel-connection layout, if the absorber was placed in the living room (3A) or in the front bedroom (3B), oriented to the sound source, these locations showed a similar noise reduction. In addition, if the absorber was simultaneously placed in both rooms, the low-frequency noise level could be effectively controlled. Figure 5 shows the noise reduction and loud-quiet difference. The noise reduction obtained by placing a 12.5 m^2 absorber in the living room was equivalent to that obtained by placing a 5 m^2 absorber in the front bedroom or a 22.5 m^2 absorber in the rear bedroom (3C). As shown in Figure 5a, when the absorber was either in the living room or the front bedroom, the noise reduction was generally the same (approximately 4 dB). However, when absorber was placed in the living room and the front bedroom, the noise reduction was the highest (up to 7.3 dB), as demonstrated in Figure 5c. This may be because the sound energy in the rear bedroom can originate from the living room and the front bedroom simultaneously. When only one of the two rooms was arranged with the absorber, sound energy could still transmit into the rear bedroom through the other room with lower damping. Consequently, the noise reduction was not as high as expected [43]. The loud-quiet difference is expected to be smaller when the front bedroom also had the absorber. In particular, when all absorbers were in the front bedroom, the difference was significantly low (only 5.3 dB), approximately 4 dB lower than that obtained when the absorber was in the living room. Similarly, if the two rooms with the absorber included the front bedroom, a loud-quiet difference of nearly 3 dB lower was observed. At 800 Hz, the absorber caused a uniform noise reduction of 4.9 dB. However, placing the absorber in the living room and in the front bedroom remained the best option (7.1 dB).



(a) Absorber in one room, 100–200 Hz

(b) Absorber in one room, 800 Hz

(c) Absorber in two rooms, 100–200 Hz

(d) Absorber in two rooms, 800 Hz

Fig. 5. Noise reduction when the absorber is in different rooms in a typical series-parallel connected layout (line: noise reduction; error bar: ±1/2 loud–quiet difference; horizontal reference line: noise reduction obtained from the average distributed location in two rooms) at the typical frequencies of 100–200 Hz and 800 Hz.

Effects of the absorption area

Figure 6 shows the curves of the noise reduction and loud-quiet difference with the absorption area in a typical series-connected layout. Noise reduction generally increased by approximately 0.3–0.5 dB/m^2 with an absorption area of 7.5 m^2; subsequently, it increased by less than 0.2 dB/m^2 in most cases, or plateaued. Conversely, the loud-quiet difference showed an increasing trend with the absorption area in the living room and a decreasing trend in the bedroom oriented toward the sound source, on comparing the first and second diagrams of Figure 6b. The series-parallel connection between rooms may contribute to the opposite trends. When the absorber reduces the SPL in the front bedroom, which is the noisiest section, and the resulting noise reduction in the rear bedroom is not as large as expected, the loud-quiet difference will decrease. With the absorption area in RL1, the noise reduction increased by 0.5 dB/m^2 until a 7.5 m^2 absorber was used, and then increased by less than 0.2 dB/m^2. Conversely, the loud-quiet difference decreased by 1.5 dB. Unlike RL1, the noise reduction continuously increased up to 4.2 dB with the absorption area in RL2 and the loud-quiet difference increased by 1.7 dB. The effect of the absorption area in RL3 was minimal (approximately 0.2 dB/m^2) after 7.5 m^2. However, it increased faster than with the absorption area in RL2 (second and third diagrams of Figure 6a). In addition, in RL3, the loud-quiet difference fluctuated around 9 dB as the absorption area increased, which may be because of the location of the quiet section. Corresponding to Hopkins' results, the quiet section was located in Room 1B, in which the length was considerably longer than the other two dimensions, rather than in Room 1C [42]. Consequently, the absorber in Room 1C was less likely to contribute to loud-quiet difference. Moreover, the curve tends to reach a plateau before 7.5 m^2 and in the range of 11.25–15 m^2 absorption area before the noise reduction increased again (second diagram of Figure 6a), which may be because the location of the additional absorber was close to the nodes of some local modes. Hence, the additional absorber may not attenuate adequate low-frequency noise as expected. Some cases have recorded negative noise reductions when the absorber was in the rear bedroom because some of the tested rooms were overdamped before fully installed with absorber; therefore, a continuous increase in the absorption area did not increase the noise reduction. Conversely, distinct changes in boundary damping and spatial shape changed the phase of

doi:10.1016/j.apacoust.2021.108465

reflected waves and local modes of the room, especially at low-frequency. Consequently, the noise reduction fluctuated slightly within 1 dB after overdamping instead of increasing continuously. This phenomenon may occur in acoustically small rooms (<200 m^3) at low frequency, where the sound field cannot be simplified as diffuse. A similar tendency was observed at 800 Hz, despite the loud-quiet difference increase of 3 dB with the absorption area in RL3.

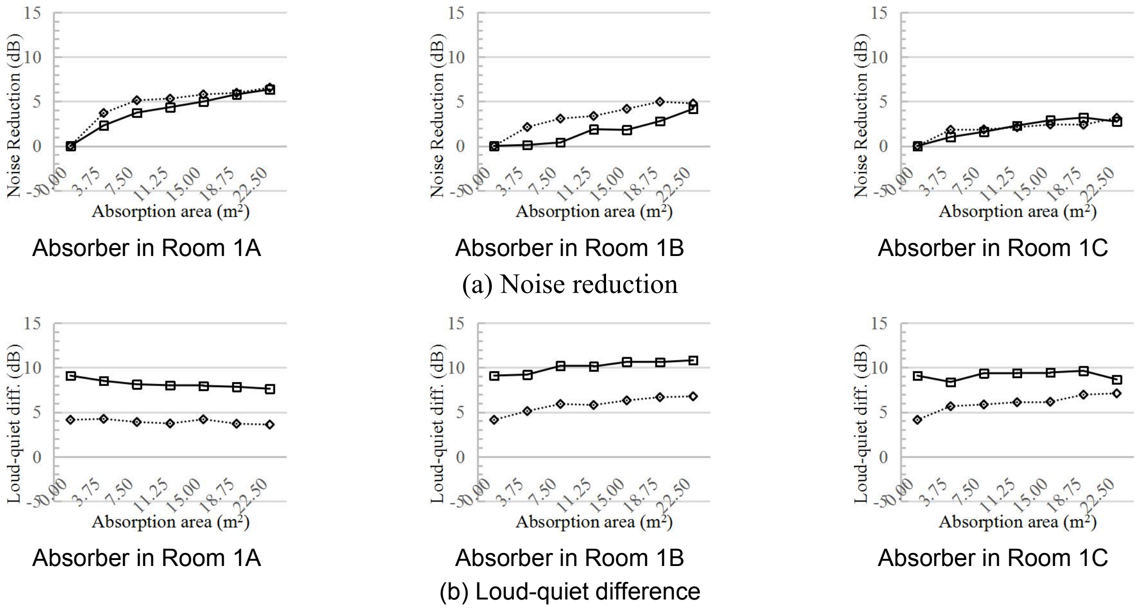


Fig. 6. Noise reduction and loud-quiet difference for different absorption areas in a typical series-connected layout at the typical frequencies of 100–200 Hz (solid line) and 800 Hz (dotted line).

The curves of the noise reduction and loud-quiet difference function of the absorption area in a typical parallel-connected layout are shown in Figure 7. The noise reduction shows similar trends, whereas the loud-quiet difference shows different trends in each parallel-connected room. The noise reduction increased continuously up to 1.8 dB until the absorption area reached 7.5 m^2, and then increased gradually by less than 0.1 dB/ m^2. The loud-quiet difference increased from 6.6 dB to 9.5 dB with the absorption area in Room 1B. Conversely, the value increased gradually up to 7.3 dB and then declined to 6.4s dB. The noise reduction and the loud-quiet difference showed a similar trend at 800 Hz and 100–200 Hz.

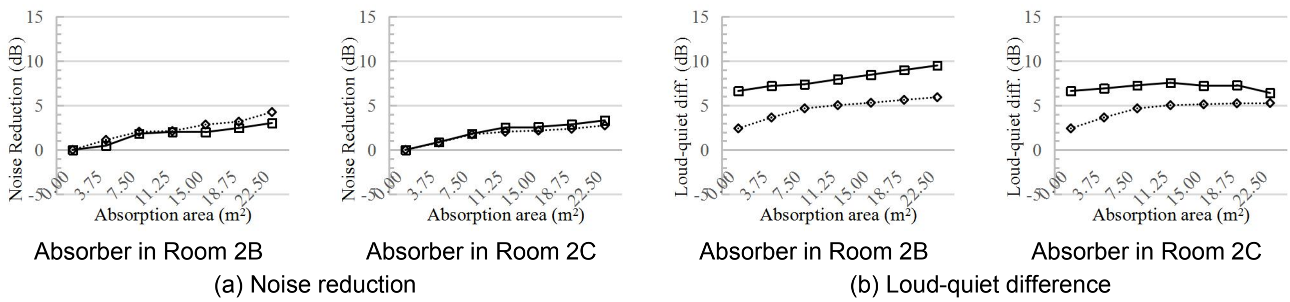


Fig. 7. Noise reduction and loud-quiet difference for different absorption areas in a typical parallel-connected layout at the typical frequencies of 100–200 Hz (solid line) and 800 Hz (dotted line).

doi:10.1016/j.apacoust.2021.108465

In a typical series-parallel-connection layout, the curves of the noise reduction and loud-quiet difference with the absorption area are shown in Figure 8. With the absorption area in the front bedroom, the noise reduction increased faster than in the living room until it reached a plateau. The loud-quiet difference showed opposite trends with absorption area in these two rooms: it increased from 2.0 dB to 9.2 dB with the absorption area in the living room, whereas it decreased to 5.3 dB (by 2.1 dB) with the absorption area in the front bedroom. This result was consistent with the results discussed earlier in Section 3.1, which indicated that the value was lower when the front bedroom had the absorber. With the absorption area in the front bedroom, the noise reduction rapidly increased to 2.4 dB by more than 0.3 dB/m^2. However, when the absorption area reached 7.5 m^2, it increased gradually (only 0.1 dB/m^2). The noise reduction increased faster with the absorption area in the front bedroom than with the absorption area in the living room before 7.5 m^2. However, the final noise reduction was the same at approximately 4 dB, as shown in the first and second diagrams in Figure 8a. When more than 7.5 m^2 absorber was used in the rear bedroom, the noise reduction increased by only 0.4 dB, while the loud-quiet difference remained almost constant due to overdamping of the room boundaries. At 800 Hz, the two indices showed similar trends; however, an increase of approximately 1 dB in the loud-quiet difference was observed with the absorption area in the front bedroom. Furthermore, unlike the results obtained for the low-frequency band, the absorption area in the rear bedroom significantly influenced the loud–quiet difference at 800 Hz. This may be related to the different location of the quiet section at different frequency bands (at the end of the living room at 100–200 Hz and in the rear bedroom at 800 Hz).

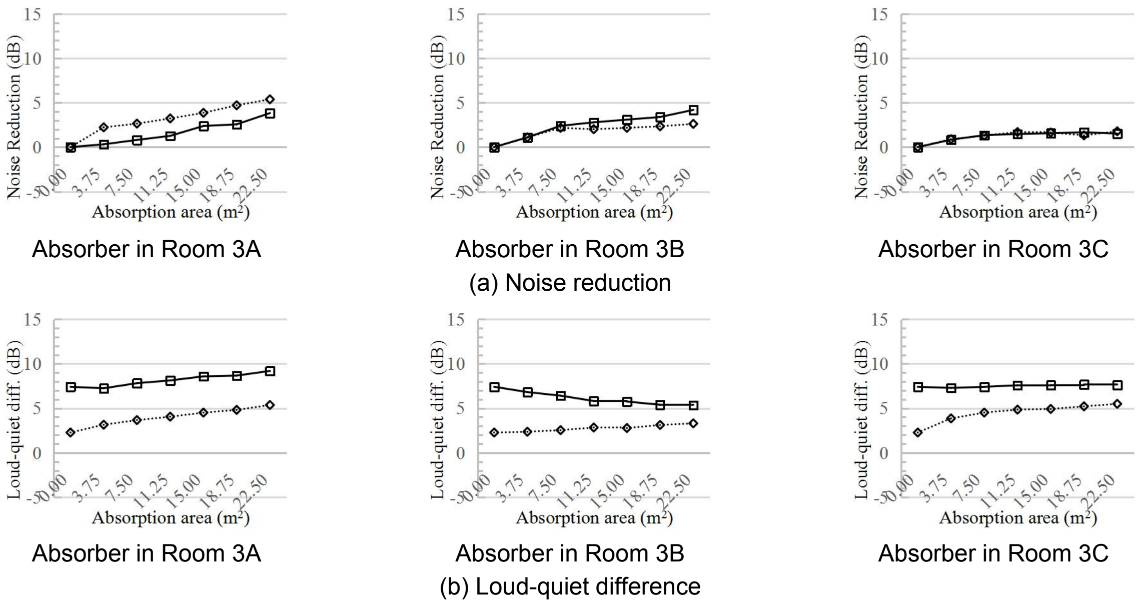
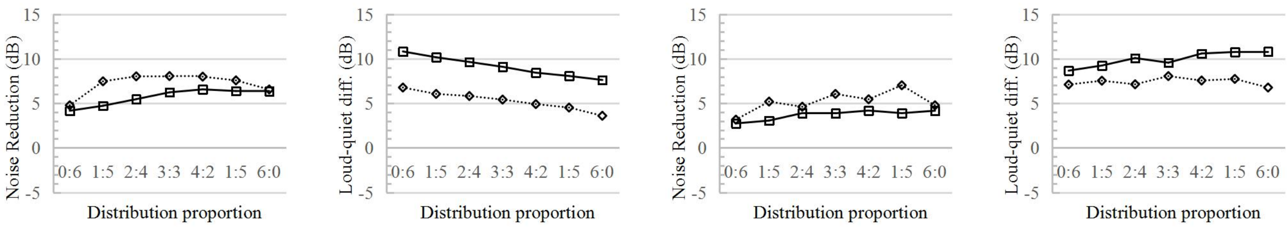


Fig. 8. Noise reduction and loud–quiet difference for different absorption areas in a typical series-parallel connected layout at the typical frequencies of 100–200 Hz (solid line) and 800 Hz (dotted line).

Effects of the absorption area distribution proportion

The trends of the noise reduction and loud-quiet difference with the absorption area distribution proportion depended on the room connection types. The distribution proportion was divided into seven intervals from 0:6 to 6:0. When the proportion of the absorber in the living room increased, the loud-quiet difference gradually increased by 3.9 dB. Noise reduction was higher with an intermediate proportion value, i.e. 1:5–5:1, than with extreme proportion values (0:6 or 6:0) wherein the noise reduction varied up to 1.8–3.4 dB. Figure 9 shows the curves of the noise reduction and loud-quiet difference with the absorption area distribution proportion between two series-connected rooms. In Section 3.1, it has been concluded that placing absorber simultaneously in RL1 and RL2 was the best configuration for a typical series-connection layout. This section mainly focuses on the absorption area distribution proportion between these two rooms. The noise reduction increased with the proportion until it peaked at 6.6 dB when the proportion was 4:2, after which the noise reduction decreased. Because the living room (RL2) was connected with all the other rooms through door openings, chances of the sound waves reflecting on the boundaries in the living room were more. Therefore, the RL1 room, with the highest sound energy radiation per unit area of boundary surface, did not necessarily have the highest absorption and the two rooms had similar absorption amounts in the proportion range of 3:3–5:1. The proportions between 3:3 and 5:1 could be ideal for noise reduction, as shown in the first diagram in Figure 9a, ensuring a negligible variation (less than 0.5 dB). The loud-quiet difference increased from 7.6 dB to 10.8 dB with the increase in the proportion. Similar trends were also observed between RL2 and RL3. At 800 Hz, the trends of the two indices were similar to those obtained at low frequencies between RL1 and RL2 but differed from those obtained between RL2 and RL3, as noise reduction fluctuated with the proportion.

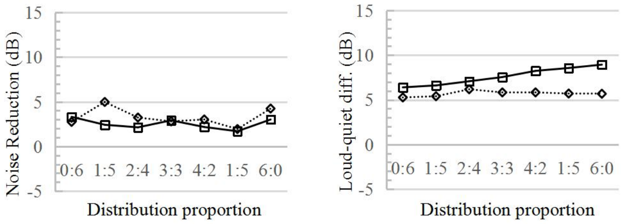


(a) Absorber in Rooms 1A-1B (b) Absorber in Rooms 1B-1C

Fig. 9. Noise reduction and loud-quiet difference for absorption area distribution proportion between typical series-connected rooms at the typical frequencies of 100–200 Hz (solid line) and 800 Hz (dotted line).

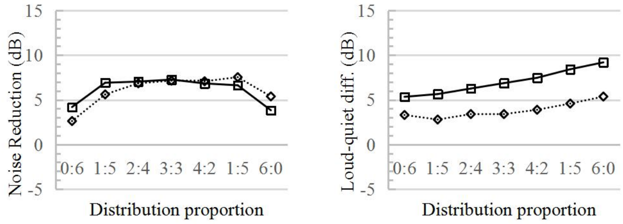
Figure 10 shows the curves of noise reduction and loud-quiet difference for two parallel-connected rooms. The noise reduction generally fluctuated around 2.5 dB. The maximum noise reduction (over 3 dB) occurred when the absorption area distribution proportion was 6:0 or 0:6, that is, when the absorber was only in one room. This may be related to the relatively small effect of the absorber in one parallel-connected room on the SPL in the other room. The noise reduction in the layout is therefore, generally determined by the slope of noise reduction with absorption area in each room. Because the slopes in the two rooms were close, the noise reduction fluctuated within a small range of only 0.4 dB. The loud-quiet difference increased by 2.5 dB with the proportion between Room 2B and Room 2C (Figure 10b). This might be related to the the quiet section located in Room 2B, and consequently the higher proportion in this room were more likely to cause higher loud-quiet difference [42]. The results at 800 Hz differed from those obtained at low frequencies because the noise reduction did not show a distinct trend and the loud-quiet difference generally remained constant around 5–6 dB.

Figure 11 shows the curves of noise reduction and loud-quiet difference for two series-parallel-connected rooms. As placing absorber simultaneously in the living room and front bedroom is the optimal configuration for a typical series-parallel-connection layout, as suggested in Section 3.1, this section mainly focuses on the absorption area distribution proportion between these two rooms. Noise reduction increased up to approximately 7 dB with the proportion, after which it remained constant as the proportion ranged from 5:1 to 1:5 (variation ≤ 0.5 dB). Conversely, the loud-quiet difference increased by up to 3.9 dB with the proportion. When the 22.5 m^2 absorber was placed in the living room, the loud-quiet difference peaked at 9.2 dB. At 800 Hz, the noise reduction was the highest (7.5 dB) when the proportion between these two rooms was 5:1. The loud-quiet difference showed a similar trend to that obtained at low frequencies.



(a) Noise reduction (b) Loud-quiet difference

Fig. 10. Noise reduction and loud-quiet difference for different absorption area distribution proportion between typical parallel-connected rooms (2B–2C) at the typical frequencies of 100–200 Hz (solid line) and 800 Hz (dotted line).



(a) Noise reduction (b) Loud–quiet difference

Fig. 11. Noise reduction and loud-quiet difference for different absorption area distribution proportion between typical series-parallel connected rooms (3A–3B), at typical frequencies of 100–200 Hz (solid line) and 800 Hz (dotted line).

Optimal absorber location

Table 4 summarises the optimal and worst locations for the noise reduction and loud-quiet difference. These values were obtained by analysing the effects of rooms with the absorber, absorption area, and proportion between its distributions on the low-frequency noise control in the residential layouts. The best place for the absorber was in the rooms at lower levels to ensure optimal noise reduction, which could consequently reduce the noise level in the rooms at higher levels. When noise entered the rear bedroom from multiple rooms, the absorber should be located in these rooms simultaneously. In addition, the absorption area within 7.5 m^2 was relatively efficient for low-frequency noise control, according to the results in Section 3.2.

The living room is the best place for an absorber to achieve an optimal loud-quiet difference at low frequency. This might be because the living room is connected to most of the rooms in a layout; thus, an absorber in this room better contributes to achieving a quiet section. Conversely, placing an absorber in the rooms at lower room levels is expected to be the worst solution to achieve an optimal loud-quiet difference.

Table 4.
Optimal and worst location of the absorber in typical series, parallel, and series-parallel connection layouts

Room connection	Indices	Optimal location		Worst location	
		Room with absorber	Value	Room with absorber	Value
Series connection	Noise reduction (dB)	2A–2B	6.6	2C	2.7
	Loud-quiet difference (dB)	2B	10.8	2A–2C	1.9
Parallel connection	Noise reduction (dB)	1C	3.3	1B–1C	1.7
	Loud-quiet difference (dB)	1C	8.9	1B	6.4
Series-parallel connection	Noise reduction (dB)	2A–2B	7.3	2C	1.5
	Loud-quiet difference (dB)	2A	9.2	2B	5.3

The optimal location for an absorber in typical series, parallel, and series-parallel connection layouts could be improved by analysing the noise reduction curve with the absorption area distribution proportion. A comparable absorption area distribution proportion between the living room and the bedroom, where noise enters first, was found optimal for low-frequency noise control. It was optimal for a typical series-connection layout to simultaneously place an absorber in RL1 and RL2 with a proportion of 3:3, achieving a noise reduction and loud-quiet difference of 6.2 dB and 9.1 dB, respectively. As the proportions between 3:3 and 5:1 may result in an ideal noise reduction (variation ≤ 0.5 dB) and the loud-quiet difference decreases with the proportion, 3:3 represents the ideal proportion for both indices. Furthermore, for a typical parallel-connection layout, placing the absorber only in the room with one dimension considerably longer than the other two could be the optimal solution. As a result, the noise reduction and loud-quiet difference would be approximately 3.0 dB. For a typical series-parallel-connection layout, placing the absorber in the living room and front bedroom with a 4:2 proportion leads to optimal performance. In particular, the noise reduction and loud-quiet difference were 6.8 dB and 7.5 dB, respectively. The comparable proportion was likely to be more optimal, which is consistent with the higher efficiency of the absorption area within 7.5 m^2 as described in Section 3.2.

4. Conclusions

In-situ measurements of typical series, parallel, and series-parallel connection dwelling layouts demonstrated the effects of rooms with the absorber, absorption area, and absorption area distribution proportion on low-frequency noise control. The results indicated optimal absorber locations for the measured layout types. The conclusions of this research are as follows:

(1) The presence of absorber in more than one room did not ensure optimal performance. In series and series-parallel connection layouts, the noise reduction obtained by placing a 5–6 m^2 absorber in the bedroom, where the noise entered initially was equivalent to that obtained by placing a 22.5 m^2 absorber in the farthest bedroom from the sound source.

(2) Noise reduction increased by 0.3–0.5 dB/m^2 with absorption area until a 7.5 m^2 absorber was used, and then increased by less than 0.2 dB/m^2 in most cases or was overdamped. The loud-quiet difference, which represents the standard deviation of the SPL in the layout, showed an increasing trend with the absorption area in the living room and a decreasing trend in the bedroom oriented to the sound source.

(3) Noise reduction was constantly high value (approximately 6–7 dB) when the absorption area distribution proportion between the living room and the bedroom oriented to the sound source was in the range of 1:5–5:1 and the variation was up to 2–3 dB in series and series-parallel connection layouts. The loud-quiet difference increased continuously by 4 dB with the proportion.

(4) Placing an absorber in the living room and the bedroom oriented to the noise source in

a relatively comparable absorption area distribution proportion (3:3–4:2) is the optimal solution for both low-frequency noise reduction and loud-quiet difference (6–7 dB and 8–9 dB, respectively).

This research provides clear evidence for low-frequency noise control through acoustic absorber location in dwelling layouts. As reported in Section 2.5, further measurements could be performed at lower frequencies. Furthermore, the results have been obtained for measurements performed in the most typical layouts with series, parallel and series-parallel room connection in China. Future studies should therefore be conducted on other worldwide common layouts. This study demonstrated the effect of absorber location on low-frequency noise control. Moreover, future studies can focus on the relationships between loud-quiet difference and subjective noise level.

Acknowledgements

This work was supported by the State Natural Science Foundation of China [grant number 51778169].

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.

References

[1] Murphy E, King EA. An assessment of residential exposure to environmental noise at a shipping port. Environ Int 2014;63(3):207–15. https://doi.org/10.1016/j.envint.2013.11.001.

[2] Persson K, Rylander R. Disturbance from low-frequency noise in the environment: A survey among the local environmental health authorities in Sweden. J Sound Vib 1988;121(2):339–45. https://doi.org/10.1016/S0022-460X(88)80034-8.

[3] Yu P, Zhai G, Huang Y, Zhang B. The analysis of noise frequency characters of facilities in urban residential area. China Environ Sci 2006;26(4):491–95 (in Chinese).

[4] Schmidt JH, Klokker M. Health effects related to wind turbine noise exposure: A systematic review. PLoS One 2014;9(12):e114183. https://doi.org/10.1371/journal.pone.0114183.

[5] Baliatsas C, Van KI, Van PR, Yzermans J. Health effects from low-frequency noise and infrasound in the general population: Is it time to listen? A systematic review of observational studies. Sci Total Environ 2016;557–8:163–169. https://doi.org/10.1016/j.scitotenv.2016.03.065.

[6] Leventhall G, Pelmear P, Benton S. A review of published research on low frequency noise and its effects. London: UK Department for Environment, Food & Rural Affairs 2003. https://doi.org/EPG1/2/50.

[7] Persson K, Bjorkman M, Rylander R. An experimental evaluation of annoyance due to low frequency noise. J Low Freq Noise Vib Act Control 1985;4:145–53. https://doi.org/10.1177/026309238500400401.

[8] Persson K, Bjorkman M, Rylander R. Loudness, annoyance and the dBA in evaluating low frequency sounds. J Low Freq Noise Vib Act Control 1990;9:32-45. https://doi.org/10.1177/026309239000900104.

[9] Møller H. Annoyance of audible infrasound. J Low Freq Noise Vib Act Control 1987; 6:1–17. https://doi.org/10.1177/026309238700600101.

[10] Inukai Y, Taya H, Yamada S. Thresholds and acceptability of low frequency pure tones by sufferers. J Low Freq Noise Vib Act Control 2005;24:163–70. https://doi.org/10.1260/026309205775374433.

[11] Qin Y,Wang B. Sound insulation of building elements. In: Duan C, editor. Architecture sound environment. 2nd ed, Beijing: Tsinghua University Press, 2000, p. 48–63 (in Chinese).

[12] Berglund B, Hassmén P, Job RF. Sources and effects of low-frequency noise. J Acoust Soc Am 1996;99(5):2985–3002.

[13] Verheijen E, Jabben J, Schreurs E, Smith KB. Impact of wind turbine noise in the Netherlands. Noise Health 2011;13(55):459–63.

[14] Tang SK. A review on natural ventilation-enabling facade noise control devices for congested high-rise cities. Appl Sci 2017;7(2):175. https://doi.org/10.3390/app7020175.

[15] Van Renterghem T, Dick B. Focused study on the quiet side effect in dwellings highly exposed to road traffic noise. Int J Environ Res Public Health. 2012;9(12):4292–310. https://doi.org/10.3390/ijerph9124292.

[16] De Kluizenaar Y, Janssen SA, Vos H, Sslomons EM, Zhou H, Van den Berg F. Road traffic noise and annoyance: A quantification of the effect of quiet side exposure at dwellings. Int J Environ Res Public Health. 2013; 10(6):2258–70. https://doi.org/10.3390/ijerph10062258.

[17] Öhrström E, Skånberg A, Svensson H, Gidlof-Gunnarsson A. Effects of road traffic noise and the benefit of access to quietness. J Sound Vib 2006;295(1–2):40–59. https://doi.org/10.1016/j.jsv.2005.11.034.

[18] Tong YG, Tang SK, Kang J, Fung A, Yeung MKL. Full scale field study of sound transmission across plenum windows. Appl Acoust 2015;89:244–53. https://doi.org/10.1016/j.apacoust.2014.10.003.

[19] Song Y, Kang J. Factors influencing low-frequency noise reduction in typical Chinese dwelling layouts. J Low Freq Noise Vib Act Control. 2020. https://doi.org/10.1177/1461348420942972.

[20] Bolt RH. Note on normal frequency statistics for rectangular rooms. Appl Acoust 1946;18:130–33. https://doi.org/10.1121/1.1916349.

[21] Morse PM. Vibration and sound. 2nd ed. New York: Acoustical Society of America, 1948.

[22] Russ S, Sapoval B, Haeberle O. Irregular and fractal resonators with Neumann boundary conditions: Density of states and localization. Phys Rev E 1997;55(2):1413–21. https://doi.org/10.1103/PhysRevE.55.1413

[23] Meissner M. The effect of modal localization on reverberant energy decay in a case of two acoustically coupled rooms. Arch Acoust 2006;31(Suppl.):239–45.

[24] Meissner M. Influence of wall absorption on low-frequency dependence of reverberation time in room of irregular shape. Appl Acoust 2008;69(7):583–90. https://doi.org/10.1016/j.apacoust.2007.02.004

[25] Eda K, Yasuda Y, Sakuma T. Sydney: Acoustical effects of columns, beams and furniture on sound fields in small enclosures. Proceedings of the 20th International Congress on Acoustics ICA 2010.

[26] Xie H, Kang J. Sound field of typical single-bed hospital wards. Appl Acoust 2012; 73(9):884–92. https://doi.org/10.1016/j.apacoust.2012.03.005.

[27] Siu-Kit L, Powell EA. Effects of absorption placement on sound field of a rectangular room: A statistical

approach. J Low Freq Noise Vib Act Control 2018;37(2):394–406. https://doi.org/10.1177/1461348418780027.
[28] Okuzono T, Sakagami K. Room acoustics simulation with single-leaf microperforated panel absorber using two-dimensional finite-element method. Acoust Sci Technol 2015;36(4):358–61. https://doi.org/10.1250/ast.36.358.
[29] Okuzono T, Sakagami K. A finite-element formulation for room acoustics simulation with microperforated panel sound absorbing structures: Verification with electro-acoustical equivalent circuit theory and wave theory. Appl Acoust 2015;95:20-6. https://doi.org/10.1016/j.apacoust.2015.02.012.
[30] Okuzono T , Sakagami K. A frequency domain finite element solver for acoustic simulations of 3D rooms with microperforated panel absorbers. Appl Acoust 2018;129:1–12. https://doi.org/10.1016/j.apacoust.2017.07.008.
[31] Maluski SPS, Gibbs BM. Application of a finite-element model to low-frequency sound insulation in dwellings. J Acoust Soc Am 2000;108(4):1741–51. https://doi.org/10.1121/1.1310355.
[32] Kang J. Acoustics in long enclosures with multiple sources. The Journal of the Acoustical Society of America 1996;99 (2):985-989. https://doi.org/10.1121/1.414627.
[33] Kang J. A method for predicting acoustic indices in long enclosures. Applied Acoustics 1997;51 (2):169-180. https://doi.org/10.1016/S0003-682X(96)00062-X.
[34] Yang T, Kang J. Sound attenuation and reverberation in sequential spaces: An experimental study. Applied Acoustics 2021;182, 108248. https://doi.org/10.1016/j.apacoust.2021.108248.
[35] Zhou Y. Detailed design of dwellings. Beijing: China Architecture & Building Press; 2006, p.76–152 (in Chinese).
[36] Zhou Y. Detailed design of dwellings II. Beijing: China Architecture & Building Press; 2015, p.48–65 (in Chinese).
[37] Schroeder MR. Frequency-correlation functions of frequency responses in rooms. J Acoust Soc Am 1962;34(12):1819–23. https://doi.org/10.1121/1.1909136.
[38] ISO 354:2003. Acoustics - Measurement of sound absorption in a reverberation room.
[39] ISO 266:1997. Acoustics – Preferred frequencies.
[40] ISO 29955: 2021. Acoustics – Acoustic quality of open office spaces.
[41] ISO 10140-4:2010. Laboratory measurement of sound insulation of building elements – Part 4: Measurement procedures and requirements.
[42] Hopkins C. Sound Insulation. Oxford: Elsevier Ltd.; 2007, p.17–74, p.224–236 and p.340.
[43] Kuttruff H. Room Acoustics. London and New York: Spon Press; 2009, p. 83–91
[44] Neubauer RO, Kang J. A Subjective Related Measure of Airborne Sound Insulation. International Journal of Acoustics and Vibration 2017; 22(2):201–10. 10.20855/ijav.2017.22.2465.