OCTOBER 04 2024

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*J. Acoust. Soc. Am.* 156, 2155–2168 (2024)
https://doi.org/10.1121/10.0030407

JASA ARTICLE

# A feasibility study on active sound reduction across an acoustic plenum window by cancelling source clusters on internal periphery of the window cavity

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**ABSTRACT:**

The possibility of applying active control to reduce sound transmission across a practical plenum window is examined experimentally in the present study using measured transfer functions of all related sound transmission paths. As a result of the limited space within the window, the error microphones are located at the indoor window opening while the secondary cancelling sources are mounted along the periphery of the window void. Results show that the cancelling sources near the outdoor window opening corners and within the overlapping region of the window play more useful roles in the control. Also, the highest sound reduction is around 6 dB with six error microphones positioned either at the central region or along the periphery of the indoor window opening. However, the results with the central error microphones suggest the possibility of adopting a dual control system to enhance the low frequency performance. Control systems with fewer error microphones result in lower sound reduction. Besides, it is found that four cancelling sources, located around the outdoor opening of the window, will be enough to achieve meaningful active sound transmission reduction between 100 and 1000 Hz. Involving more cancelling sources does not result in better performance despite the added complexity. 
https://doi.org/10.1121/10.0030407

(Received 1 May 2024; revised 19 August 2024; accepted 16 September 2024; published online 4 October 2024)

[Editor: Francesco Aletta] Pages: 2155–2168



## I. INTRODUCTION

Mitigating noise pollution in densely populated high-rise cities has long been a challenge to government officials, engineers, and academics.[1] The very limited useable urban land space has resulted in residential buildings being erected near main traffic trunk roads and train lines. Noise intrusion into residential units can be a big problem if proper mitigation measures are not taken. Roadside barriers[2] and noise screening building clusters[3] are not applicable because of the shortage of land area. Extended podia and setbacks[4] reduce the number of residential units that, theoretically, can be built and, thus, are not solutions to the problem. The balconies on building façades cannot help either as the multiple sound reflections within the balcony voids could worsen the situation unless sound absorbent materials are installed.[5,6] Double-grazing windows[7] cannot help as they adversely affect indoor ventilation effectiveness unless a mechanical ventilation system is installed. However, such a system results in additional energy consumption and is not recommended. A system that can offer sufficient noise isolation while allowing for a reasonable natural ventilation rate is urgently required.

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An acoustic plenum window, also known as a ventilation window or plenum window, has been proposed for this purpose.[8,9] This window type is a partially opened double-grazing window. Its two openings are on opposite sides of the window, and the void between the two window panes and two openings provides the air passage, allowing natural ventilation of a residential unit provided that means for cross-ventilation is made available. An *in situ* measurement of Tong *et al.*[10] shows that the plenum windows can give ∼8–9 dBA higher traffic sound reduction than the conventional side-hung window of minimum allowable opening size. Li *et al.*[11] have developed an empirical formulation for predicting the noise reduction of dual and triple plenum windows. There are also efforts on numerical prediction of the sound transmission loss across a plenum window. Typical examples include Du *et al.*[12] and Yu *et al.*,[13] but this list is by no mean exhaustive.

There have also been efforts that attempt to improve the sound reduction of plenum windows. Lee *et al.*,[14] Tang,[15] and Li *et al.*[16] investigate the use of sonic crystals, and Fusaro *et al.*[17] propose a type of meta-material for this purpose. Although the method of active noise control[18] needs electrical power to operate, it appears to be an interesting alternative as vanishing sound pressures at some locations along the sound transmitting paths could imply an overall reduction of sound transmission across the window. There are already research efforts on its use to reduce sound transmission across traditional open windows.[19,20] Huang *et al.*[21] experimentally implement the active reduction of sound transmission across a scaled-down plenum window. Impressive active noise reduction is achieved at frequencies below 400 Hz. However, their setup is not likely to apply to domestic residential units because their control sources are installed within the window void, substantially increasing the flow resistance of the void and adversely impacting daylight penetration. The recent results of Wang *et al.*[22] show the effectiveness of active noise reduction across a duct-like staggered window installed with resonators. This setup is probably very good for cold or moderate cold climate regions, where keeping warm is of higher priority than natural ventilation. Tan *et al.*[23] also studied the use of active control to reduce sound transmission across a plenum window. Again, their long plenum design is not so favorable to natural ventilation. In tropical and subtropical regions, the dimensions of the plenum windows of Tong *et al.*[10] and Li *et al.*[11] appear much more realistic. Plenum windows with dimensions similar to those of the plenum window tested in the present study (presented later) have been adopted in a number of housing estates in Hong Kong (for instance, Li *et al.*[11]). Ergonomic and user interfacial provisions, which are important aspects for practical window design as pointed out by Fusaro *et al.*,[24] have been carefully considered previously, although there is always room for further improvement.

One should note that to achieve a reasonable natural ventilation rate, the separation between the two openings cannot be too long, and the two openings cannot be too small. The gap between the two window panes cannot be too wide such that it does not reduce much of the living space area. All these constraints make the implementation of active sound transmission reduction in the present study more complicated than in the cases of Huang *et al.*,[21] Wang *et al.*[22] and Tan *et al.*[23]

Tang *et al.*[25] have conducted a preliminary study on active noise reduction over a practical plenum window for subtropical region application. Using a multi-input-multi-output system consisting of three error microphones and three cancelling sources, effective active control was observed but restricted at frequencies below 400 Hz. In the present study, secondary cancelling sources are mounted on the two mullions and the ceiling of the plenum window cavity, facing the window void instead of the incoming noise as was done in Tang *et al.*[25] Error microphones are installed at the indoor window opening. A transfer function approach is adopted to understand how different combinations of error microphones and cancelling sources can affect the active sound transmission reduction, especially at frequencies above 400 Hz, which are more relevant to environmental noise intrusion problems.

It is understood that the active control system investigated in the present study tends to attenuate sound/noise across its operating frequency range non-selectively as in other similar studies (for instance, Wang *et al.*[22] and Tan *et al.*[23]). This could have an impact on indoor soundscape.[26] The corresponding effects and improvement measures are left to further investigations.

## II. THE TRANSFER FUNCTION APPROACH

We investigate the theoretical performance of active sound reduction using experimentally measured transfer functions of various sound transmission paths across the plenum window. An active noise controller was not involved in the present study and, thus, the current results can be regarded as the optimum achievable via the active control method.

Figure 1 shows the schematics of the present plenum window with dimensions and locations of error microphones and secondary cancelling loudspeakers inside the window. Hereinafter, $e_i$ denotes the $i$th error microphone, and $S_i$ are the $i$th cancelling speakers. However, five additional microphones were located inside the receiver room in the experiment for active noise reduction performance evaluation. They will be discussed later in Sec. III. It should be noted that the horizontal separation between adjacent cancelling sources on the window ceiling in the present study is 160 mm, where $S_{10}$ is on the vertical centerline of the plenum window. On the vertical mullions, $S_3$ and $S_{17}$ are on the horizontal centerline of the window. The vertical distance between adjacent cancelling sources on the mullions is 200 mm. The positions of the error microphones are aligned with the cancelling sources.

As mentioned above, the cancelling secondary sources cannot be mounted within the window void as was the case

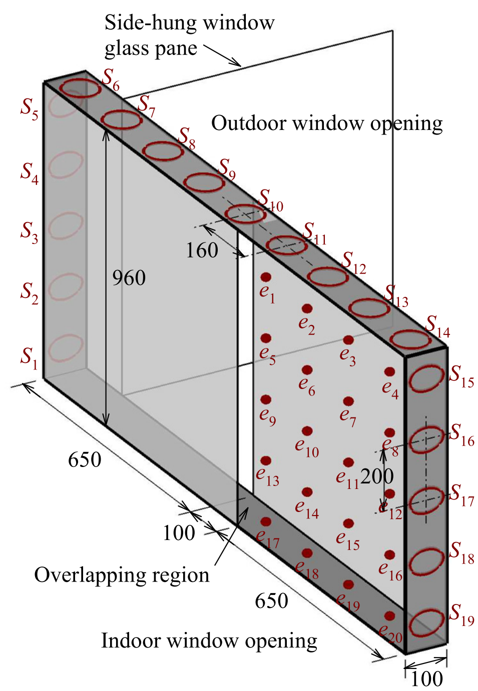



FIG. 1. (Color online) Schematics of the control assembly and dimensions of the plenum window. All dimensions are in mm. (●) Error microphones and (○) secondary cancelling loudspeakers are shown.

in Huang *et al.*[21] because of daylight issues, aesthetics, and the narrow window gap width. Also, the aperture of each cancelling loudspeaker (in the present study, model 77R34 Queen Well) is ∼3 in., which is the largest one that can be adopted for this type of plenum window. The low frequency cancellation is, therefore, not expected to be so effective at frequencies below 100 Hz. However, as the dominant traffic noise frequency range is between 200 and 2000 Hz,[27] the present setup should be acceptable for practical applications.

In total, there are 20 error microphones and 19 cancelling secondary sources available for use in the present study. Suppose $N$ number of error microphones and $M$ number of cancelling sources are selected to implement the control system. The acoustic pressure at the $i$th error microphone, $e_i$, in the presence of the primary source and cancelling sources in the frequency domain is

$$p_{e_i}(\omega) = H_{p,e_i}(\omega) S_p(\omega) + \sum_{j=1}^{M} H_{S_j,e_i}(\omega) S_{S_j}(\omega), \tag{1}$$

where $S$ denotes the strength of a sound source, $S_j$ is the $j$th cancelling source, $H_{X,Y}$ is the transfer function of the transmission path from $X$ to $Y$, and the subscript $p$ represents the quantity associated with the primary source. The target is to estimate $S_{S_j}$ such that $p_{e_i} = 0$ for all $i$. $N$ number of simultaneous equations similar to Eq. (1) can be set up, and one has in matrix format,

$$\begin{pmatrix} H_{S_1,e_1} & \cdots & H_{S_M,e_1} \\ \vdots & \ddots & \vdots \\ H_{S_1,e_N} & \cdots & H_{S_M,e_N} \end{pmatrix} \begin{pmatrix} \hat{S}_{S_1} \\ \vdots \\ \hat{S}_{S_N} \end{pmatrix} = - \begin{pmatrix} H_{p,e_1} \\ \vdots \\ H_{p,e_N} \end{pmatrix}, \tag{2}$$

where $\hat{S}_{S_j} = S_{S_j}/S_p$. The strengths of the cancelling sources can then be found once that all the transfer functions are available.

There are two parameters that can be used to describe the performance of the active control system after the cancelling source strengths are estimated. One parameter is certainly the reduction of the average squared sound pressure from the 20 error microphones (expressed as a ratio) such that

$$R_e = \sum_{i=1}^{N} \left| p_{e_i}^2 \right|_w \Big/ \sum_{i=1}^{N} \left| p_{e_i}^2 \right|_{w/o}, \tag{3}$$

where the subscripts "$w/o$" and "$w$" hereinafter denote cases without and with the active control, respectively. The other parameter represents the actual reduction of squared pressures inside the receiver room (represented by the subscript $r$),

$$R_r = \sum_{i=1}^{5} \left| p_{r_i}^2 \right|_w \Big/ \sum_{i=1}^{5} \left| p_{r_i}^2 \right|_{w/o}, \tag{4}$$

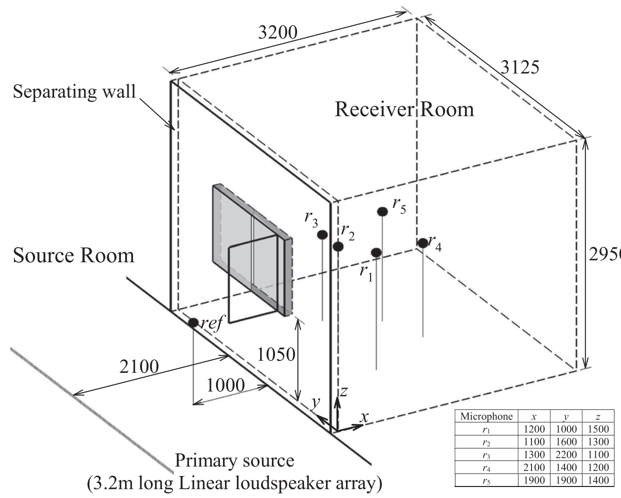
where $r_i$ denotes the $i$th microphone in the receiver room and

$$\frac{p_{r_i}(\omega)}{S_p(\omega)} = H_{p,r_i}(\omega) + \sum_{j=1}^{M} H_{S_j,r_i}(\omega) \hat{S}_{S_j}(\omega). \tag{5}$$

## III. EXPERIMENTAL SETUP

The experiment to determine the transfer functions was performed inside the Building Acoustics Testing facility of the Hong Kong Polytechnic University.[25] This dual chamber setup, structurally isolated from the main building, is designed to measure a sound transmission class of STC55. Figure 2 summarizes the experimental setup, and the physical appearance of the plenum window during the experiment is illustrated in Fig. 3. The plenum window was installed on the wall that separated the two chambers. The primary source, which was a linear array consisting of twenty 6-in. aperture JBN JX-006 loudspeakers (total length 3.2 m; Feby Electronic, Indonesia), was located 2.1 m away from the separating wall and made parallel to the plenum window in the semi-anechoic source room in the present study. The semi-anechoic source room avoids random sound incidence at the outdoor window opening, making the present study more relevant to practical conditions not within street canyons (for instance, Li *et al.*[11] and Fusaro *et al.*[28]). The loudspeaker normal axes were tilted toward the horizontal centerline of the plenum window.

The present receiver room, which was partially lined with sound absorbing material, was rectangular with dimensions as shown in Fig. 2. Five Brüel and Kjaer type 4189 1/2 in. microphones (Brüel & Kjær, Nærum, Denmark) were used inside the receiver room to measure the sound transmitted across the plenum window. Their locations followed mostly those recommended by BS EN ISO 16283-3,[29] and the current test chamber settings did not fulfil the laboratory test requirements of BS EN ISO 10140-5,[30] but they were more relevant to field studies.[11,28] Although the positions of these microphones did not follow exactly the requirements




| Microphone | $x$ | $y$ | $z$ |
|---|---|---|---|
| $r_1$ | 1200 | 1000 | 1500 |
| $r_2$ | 1100 | 1600 | 1300 |
| $r_3$ | 1300 | 2200 | 1100 |
| $r_4$ | 2100 | 1400 | 1200 |
| $r_5$ | 1900 | 1900 | 1400 |

FIG. 2. Schematics of the experimental setup and testing chambers, with (●) representing microphones. All dimensions are in mm. The sub-table illustrates the coordinates of the receiver room microphones.

https://doi.org/10.1121/10.0030407


(a) (b) (c)

FIG. 3. (Color online) The physical experimental setup, showing (a) view of the plenum window from the source room, (b) plenum window viewed from the receiver room, and (c) close up of some secondary cancelling sources.

of the two stated ISO standards (Fig. 2), a quick check has been performed with microphones located at positions conformed to the standard, and it was confirmed that the differences in average receiver room sound pressure levels were insignificant.

One additional Brüel and Kjaer type 4189 1/2 in. microphone was positioned 1 m away from the outdoor window opening at the height level of the window sill as a reference. According to BS EN ISO 3382-2,[31] the reverberation times of the receiver rooms measured are presented in Fig. 4(a). It should be noted that a highly reverberant receiver room is not to the benefit of the active control as the procedure described in Sec. II could just force a nodal plane at the indoor window opening without actually attenuating the sound inside the receiver room.

Brüel and Kjaer type 4935 1/4 in. microphones were used as the error microphones. The sound sources, including the primary source, were sounded one by one. During each operation of a sound source, all microphone signals (20 error microphones, 1 reference microphone, and 5 receiver room microphones) and the driving voltage fluctuation fed to the sound source were recorded simultaneously by a Brüel and Kjaer type 3506D PULSE recorder for later transfer function calculation. The sampling rate was 32 768 samples per channel per second. The driving voltage fluctuation represents the sound strength of a sound source in the present study and, thus, the unit of sound source $S$ in the present study is volt. White noise signals were fed to the power amplifiers, which drove the loudspeakers during the measurement. Figure 4(b) illustrates the noise spectrum recorded at the reference point when only the primary source was turned on.

## IV. RESULTS AND DISCUSSION

As there are many possible combinations of error microphones and secondary cancelling sources that can make up the noise cancellation system, the present study will focus on the cases with $N \leq 6$ as a congested microphone system will just complicate the practical implementation of the active control given the limited window space availability. The number of cancelling sources $M$ varies, but it will be shown later that there will not be many benefits to the control performance once $M$ exceeds 8 for $N \leq 6$. It should be noted that too many error microphones and/or cancelling sources will just complicate the control system without much performance improvement and are, therefore, undesirable for practical implementation.

### A. Basic sound transmission across plenum window

Figure 5 illustrates the magnitudes of $H_{\mathrm{ref},e_i}$ (without the cancelling sources), which also indicates the distribution of sound energy at the indoor exit of the plenum window when subject to a white noise excitation from the primary source. One can notice that $|H_{\mathrm{ref},e_i}| < 1$ over the whole frequency range except at very limited narrow bands at around 100 and 500 Hz. It is also observed that the plenum window is already an effective sound insulation device, although it is relatively less effective at frequencies below 500 Hz. The sound near the overlapping region of the plenum window tends to be weaker [Figs. 5(d), 5(h), 5(l), 5(p), and 5(t)] and, in general, less sound energy reaches the lower part of the indoor window opening [Figs. 5(q)–5(t)]. However, it will be demonstrated later that error microphones located within the peripheral zone of the indoor window opening can perform reasonably well, except at higher frequencies where the sound energies without the cancelling sources are already relatively weak.

Figure 6 illustrates the spectral variation of the averaged squared transfer function magnitudes over the indoor window opening and within the receiver room. These values also represent the average squared sound pressures normalized by those recorded by the reference microphone. The averaging smooths out the spurious spectral characteristics of the sound transmission, but one can still observe that the patterns resemble those from the error microphones in the

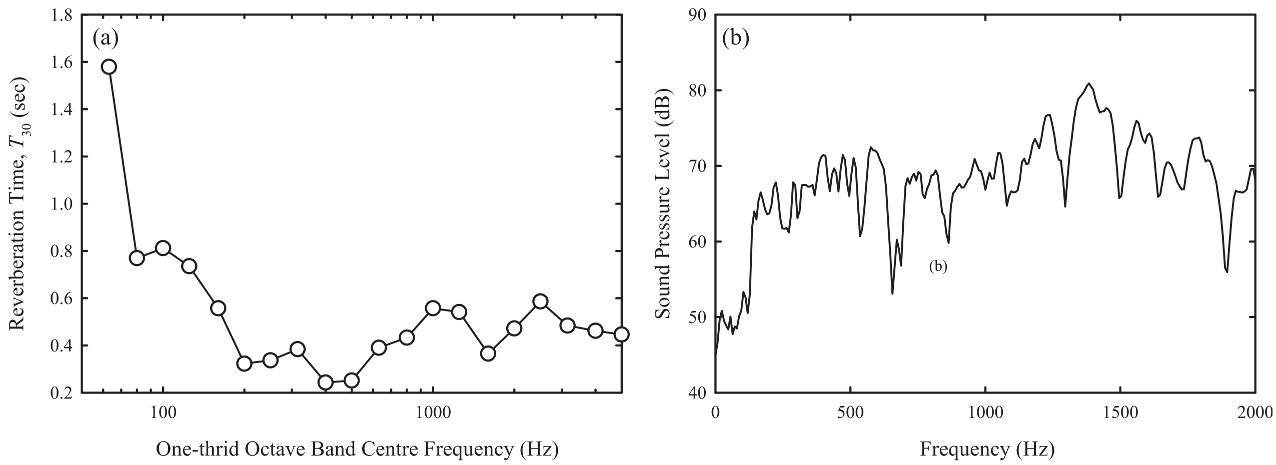



FIG. 4. (a) Reverberation times in the receiver room, and (b) the frequency spectrum of sound at the reference microphone location due to the primary source alone are depicted.

central region of the indoor window opening. The sound at high frequencies is further attenuated inside the receiver room, probably resulting from the sound absorption lining there. As the original plenum window has attenuated much of the sound at frequencies higher than 1000 Hz already, it is difficult for the cancelling sources to further attenuate these sounds in the receiver room (discussed later).

## B. Cancelling source clustering

### *1. Central error microphone array*

There are many different combinations of error microphones that can be used to perform the control. However, we shall focus on some more straightforward choices in this study. We start with $N = 6$, where the error microphones are in the central region of the indoor window opening (they are microphones $e_6$, $e_7$, $e_{10}$, $e_{11}$, $e_{14}$, and $e_{15}$). The intention is to create a low sound pressure (quiet) zone there. The spectral variations of mean squared pressures within the receiver room with all combinations of cancelling sources are calculated.

Figures 7(a), 7(b), 7(c), 7(d), and 7(e) illustrate the performances of the cancelling source clusters of [$S_{10}$], [$S_2$ $S_5$ $S_{10}$ $S_{18}$], [$S_1$ $S_2$ $S_5$ $S_{10}$ $S_{18}$], [$S_1$ $S_2$ $S_5$ $S_9$ $S_{14}$ $S_{15}$], and [$S_1$ $S_2$ $S_5$ $S_6$ $S_8$ $S_9$ $S_{15}$ $S_{17}$], respectively. Generally, there is no further sound reduction at frequencies below 100 Hz or above ~1000 Hz. The latter frequency range agrees with the inference from Figs. 5 and 6, which were discussed in Sec. IV A. Figure 7 also shows that sound reduction of the plenum window can even be lowered at higher frequencies when a quiet zone is created at the central region of the indoor window opening. This phenomenon applies to all other cancelling source clusters (not presented here). It should be noted that the cancelling source clusters in Fig. 7 are the best performers at the corresponding value of $M$ in terms of total mean squared pressure reduction between 100 and 1000 Hz. One can also infer from Fig. 7 that the acoustic performance of the clusters could be adversely affected by the increase in $M$. At $M = 6$, the sound reduction frequency range appears narrower. It is observed that the active control does not further reduce the noise levels at frequencies higher than 600 Hz in general [Fig. 7(d)]. The bandwidth of sound reduction at $M = 8$ is widened again with some improved performance at low frequencies.

To better present the overall performance of the sound reduction, we define the ratio of total sound energy within the frequency range from 100 to 1000 Hz (100 Hz $\leq f \leq$ 1 kHz) as

$$R_{r(100-1\mathrm{kHz})} = \sum_{f=100\ \mathrm{Hz}}^{1\ \mathrm{kHz}} \left( \sum_{i=1}^{5} \left| p_{r_i}^2 \right|_w \right) \Bigg/ \sum_{f=100\ \mathrm{Hz}}^{1\ \mathrm{kHz}} \left( \sum_{i=1}^{5} \left| p_{r_i}^2 \right|_{w/o} \right). \tag{6}$$

Figure 8 shows the variation of the lowest $R_{r(100\text{-}1\mathrm{kHz})}$ in dB with the number of cancelling sources in a cluster, $M$, for two error microphone arrangements. The results with the error microphone setting [$e_1$ $e_4$ $e_8$ $e_{12}$ $e_{17}$ $e_{20}$] will be discussed in Sec. IV B 2. For the present central error microphone setting, one can clearly see that there is no further sound reduction performance improvement for $M > 7$. The narrower reduction bandwidth for the $M = 6$ case [Fig. 7(d)] lowers the overall sound reduction. The bandwidth of the $M = 5$ case is wide compared with those of the others (Fig. 7), but its overall sound reduction is a bit lower than those of the $M = 4$ and 8 cases, probably because of its relatively weaker low frequency performance. It will be shown later that some $M = 4$ clusters can give a sound reduction bandwidth comparable to that of $M = 5$ depicted in Fig. 7(c). In general, $M = 4$ is acceptable as the high complexity of the $M = 7$ or 8 cluster is not desirable for practical implementation. More discussions are given below.

Table I summarizes the best four higher-achieving clusters, and the corresponding $R_{r(100\text{-}1\mathrm{kHz})}$'s are given for easy reference. One can notice from Table I that, except for the cases of $M = 1$, the sound energy reduction achieved by the best four clusters is very similar. The difference is also within experimental uncertainty.

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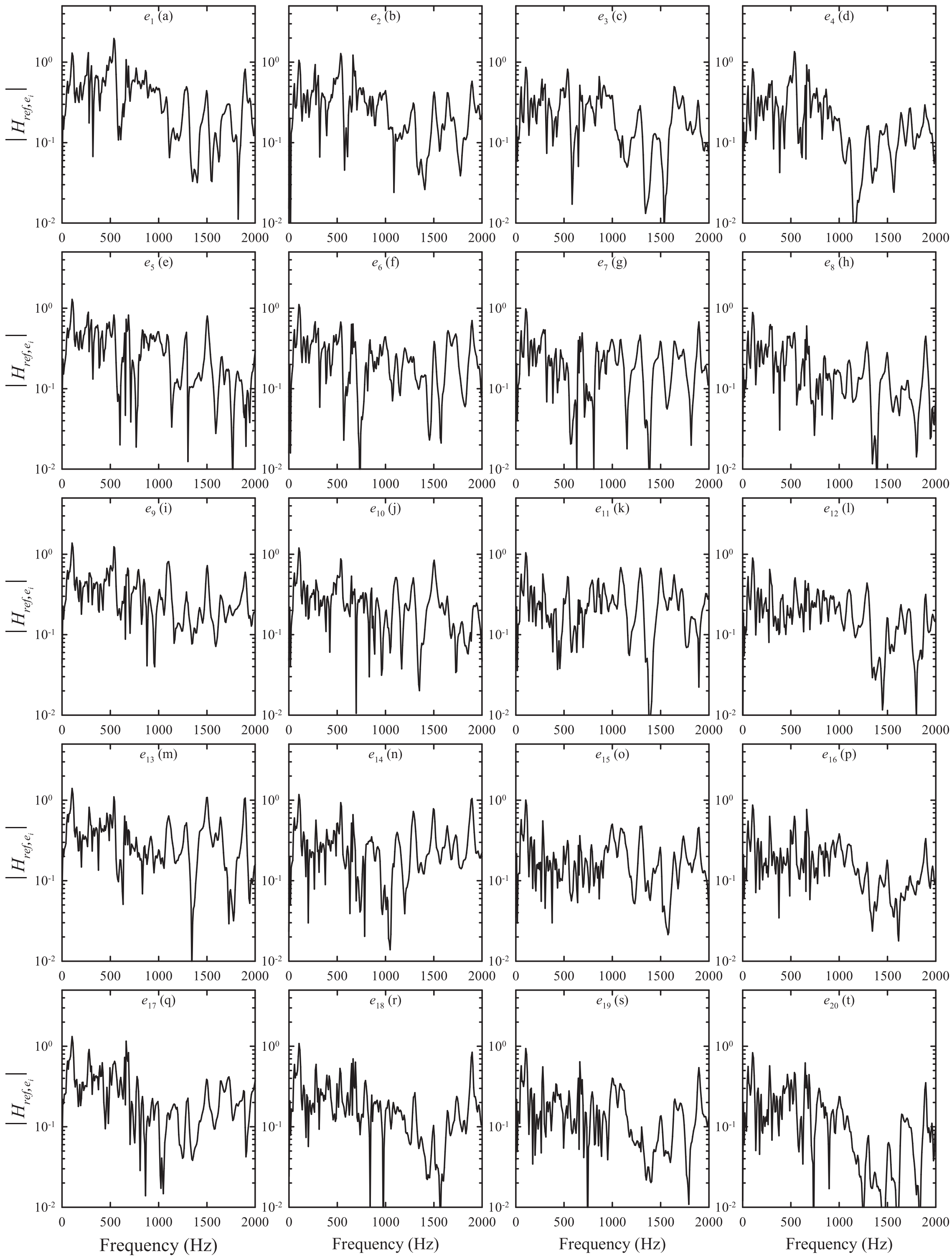


FIG. 5. Magnitudes of the transfer functions between primary source and error microphones $H_{p,e_i}$. (a) $e_1$, (b) $e_2$, (c) $e_3$, (d) $e_4$, (e) $e_5$, (f) $e_6$, (g) $e_7$, (h) $e_8$, (i) $e_9$, (j) $e_{10}$, (k) $e_{11}$, (l) $e_{12}$, (m) $e_{13}$, (n) $e_{14}$, (o) $e_{15}$, (p) $e_{16}$, (q) $e_{17}$, (r) $e_{18}$, (s) $e_{19}$, and (t) $e_{20}$ are shown.

It is interesting to note that a single $S_{10}$ can give rise to around 3 dB additional sound level reduction in the receiver room and offer good low frequency sound attenuation [Fig. 7(a)]. This cancelling source is located in the middle of the overlapping region of the plenum window and an important member of nearly all high-achieving clusters. $S_1$, $S_2$, and $S_5$ are even more important cluster members. The former two are near the window sill corner, and the last one is near the upper corner of the outdoor window opening. These positions are possible antinodal points in the absence of the cancelling sources. It should be pointed out that $S_6$, $S_8$, and $S_9$ are also good candidates to consider. When $M$ becomes

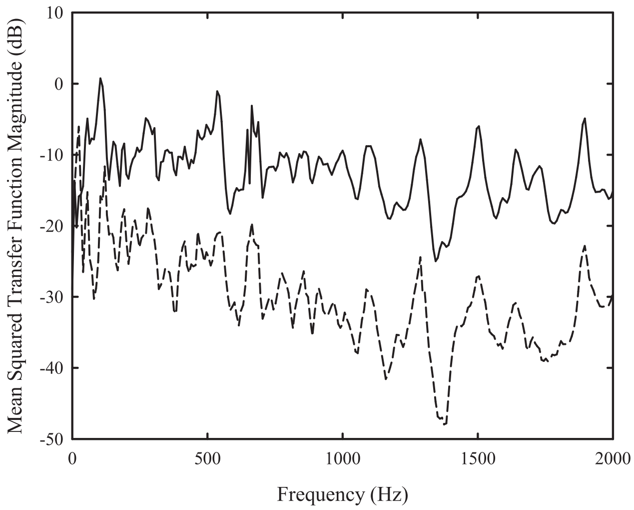


FIG. 6. Spectral variations of normalized mean squared pressures, showing (—) over indoor window exit and (– – –) within receiver room.

large, one can find more clusters involving $S_{14}$, $S_{15}$, $S_{18}$, and $S_{19}$. These sources are also near a corner of the plenum window. However, the improvement of sound reduction in the receiver room is limited despite the complexity of the clusters and within experimental uncertainty. Also, in the opinion of the authors, it is not preferable to use cancelling sources near the indoor window opening as they tend to radiate sound that interacts directly with the intruding sound inside the receiver room instead of creating a quiet zone at the indoor window opening. It is clearly depicted in Fig. 9 that the cluster [$S_1$ $S_2$ $S_5$ $S_8$] can create a much better quiet zone at the central region of the indoor window opening than the cluster [$S_2$ $S_5$ $S_{10}$ $S_{18}$]. The size of such a quiet zone is even comparable to that of the complicated cluster [$S_1$ $S_2$ $S_5$ $S_6$ $S_8$ $S_9$ $S_{15}$ $S_{17}$], which is also the best performing cluster under the central error microphone setting (Table I). It should be noted that the sound pressure magnitudes at the central error microphones in the presence of this $M = 8$ cancelling source cluster are approaching vanishing level ($\ll$0.01 Pa/V) and, thus, cannot be shown in Fig. 9.

Both the abovementioned clusters give rise to higher sound pressures at frequencies higher than 1000 Hz at the upper and lower parts of the indoor window opening, and this adds to the ineffectiveness of the possible active control at higher frequencies. The cluster [$S_1$ $S_2$ $S_5$ $S_8$] results in stronger high frequency sound pressures within the two abovementioned regions than the cluster [$S_2$ $S_5$ $S_{10}$ $S_{18}$], but the former still results in significantly lower overall sound energy between 100 and 1000 Hz, as shown in Fig. 10(a). Figure 10(b) illustrates that the sound reduction bandwidth of [$S_1$ $S_2$ $S_5$ $S_8$] is comparable to that of the best performing $M = 5$ cluster [$S_1$ $S_2$ $S_5$ $S_{10}$ $S_{18}$] and, yet, the former gives a slightly better sound reduction than the latter.

The above discussions suggest that the $M = 4$ cluster [$S_1$ $S_2$ $S_5$ $S_8$] is a better choice. As the plenum window without active control can provide good sound insulation at around 150 Hz, one can consider a dual control system introduced by Hu and Tang[32] for broadband sound insulation. The first system uses [$S_{10}$] and is operated under a low-pass filter at 150 Hz, whereas the other adopts the cluster [$S_1$ $S_2$ $S_5$ $S_8$] and handles frequencies between 150 and 1000 Hz. No control action is required at frequencies higher than 1000 Hz, mainly because of the already strong sound insulation capacity of the plenum window.

It appears that the secondary sources within the outdoor opening region of the plenum window are more effective in achieving sound attenuation. This observation tends to agree with that concluded by Tan *et al.*,[23] although the configuration of their window is very different from that of the present window. However, one secondary source is not enough for meaningful sound reduction performance in the present case.

### 2. Error microphones at the periphery of indoor window opening

Another simple choice of error microphone location is the periphery of the indoor window opening. With $N$ fixed at six, the error microphones are $e_1$, $e_4$, $e_9$, $e_{12}$, $e_{17}$, and $e_{20}$. In this case, the average separation between error microphones is longer than that of the central error microphone array discussed in Sec. IV B 1. As depicted in Fig. 5, the sound energies at $e_4$, $e_{12}$, $e_{17}$, and $e_{20}$ are relatively weaker at higher frequencies. However, it will be revealed later that the upper bound of the active sound reduction bandwidth is not lower than that achieved with the central error microphones.

The variation of the lowest total energy ratio $R_{r(100\text{-}1\text{kHz})}$ (in dB) in this peripheral error microphone case with $M$ has been shown in Fig. 8. The trend is very similar to that of the central error microphone case, but the corresponding magnitude of sound reduction is lower except when $M = 1$. The situation worsens as $M$ increases, generally, and this system does not work for $M > 16$. Interestingly, in this case, the best performing cluster is the $M = 4$ [$S_1$ $S_2$ $S_5$ $S_9$], which appears close to the results displayed in Table I. In this case of peripheral error microphones, cancelling sources near the indoor window opening are much less important (Table II). Also, for $M = 1$, only [$S_2$] can give reasonable performance. $S_1$ and $S_2$ are the most important cancelling sources under this error microphone setting. The latter appears in all higher-achieving cancelling source clusters.

The mean squared pressures inside the receiver room with the best performing clusters for $M = 1$, 4, and 8 are presented in Fig. 11. Compared with Fig. 6(a) for the $M = 1$ case, the single [$S_2$] in this case, results in less low frequency reduction but a much wider attenuation bandwidth [Fig. 11(a)] and, thus, a more significant overall sound reduction than the [$S_{10}$] in the previous case discussed in Sec. IV B 1. Performance of the cluster [$S_1$ $S_2$ $S_5$ $S_9$] [Fig. 11(b)] is comparable to that of the cluster [$S_1$ $S_2$ $S_5$ $S_8$] in the central error microphone array case [Fig. 10(b)] in terms of overall sound reduction and attenuation bandwidth. For $M \geq 5$, the drop in performance is mainly associated with the narrower sound reduction bandwidth and magnitude of reduction. An example with $M = 8$ is presented in Fig. 11(c).

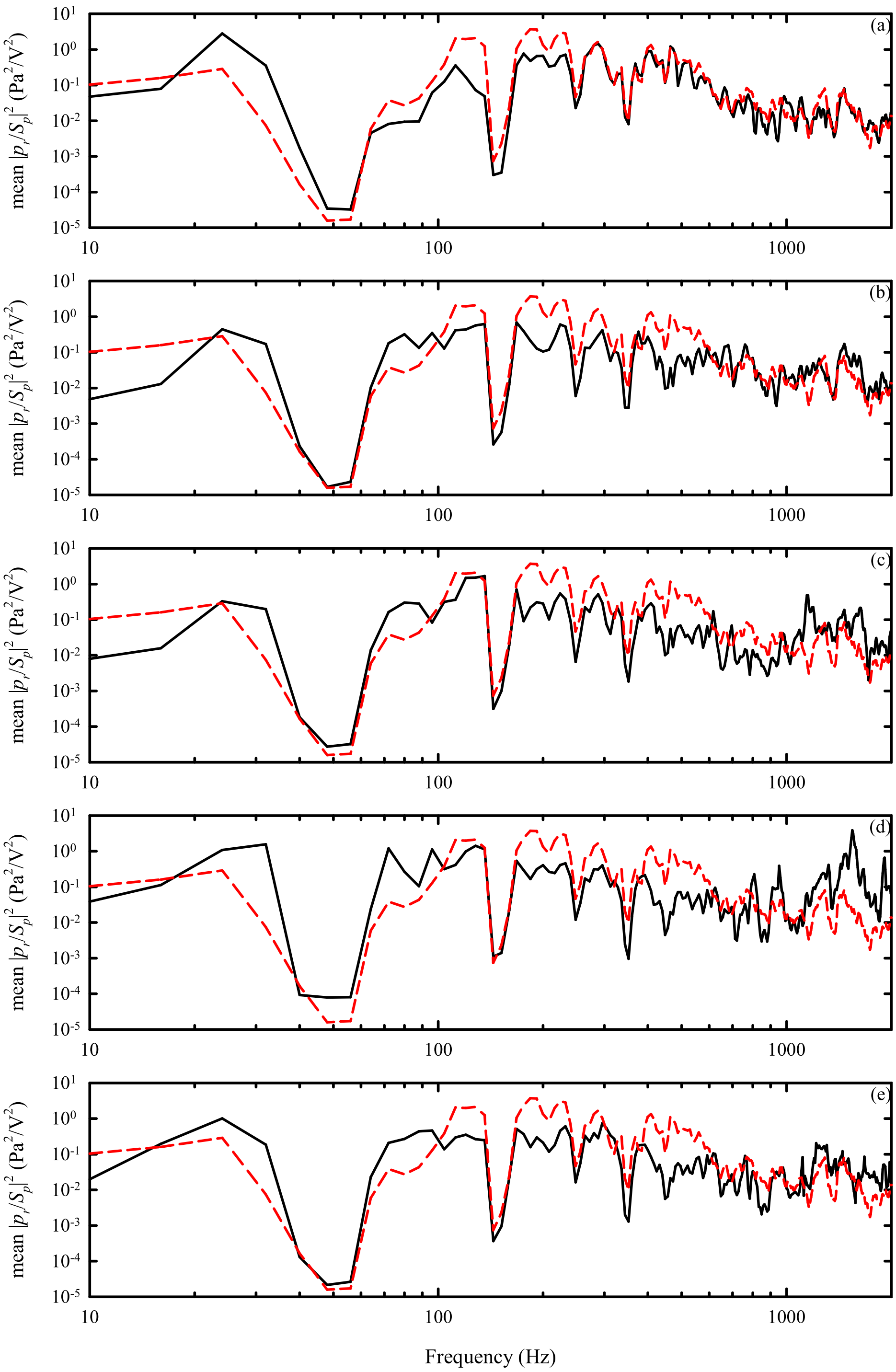


FIG. 7. (Color online) Examples of the spectral characteristics of sound reduction due to cancelling source clusters. Error microphones are $e_6$, $e_7$, $e_{10}$, $e_{11}$, $e_{14}$, and $e_{15}$, showing (a) [$S_{10}$]; (b) [$S_2$ $S_5$ $S_{10}$ $S_{18}$]; (c) [$S_1$ $S_2$ $S_5$ $S_{10}$ $S_{18}$]; (d) [$S_1$ $S_2$ $S_5$ $S_9$ $S_{14}$ $S_{15}$]; and (e) [$S_1$ $S_2$ $S_5$ $S_6$ $S_8$ $S_9$ $S_{15}$ $S_{17}$]. (—) Cancelling sources ON and (— — —) without cancelling sources are shown.



The spectral sound pressures at the 20 error microphones with the cluster [$S_1$ $S_2$ $S_5$ $S_9$] in the present peripheral error microphone setting have been presented in Fig. 9. Compared to the results of the control system with the central error microphones and the best cluster [$S_1$ $S_2$ $S_5$ $S_8$] presented in Sec. IV B 1, this control system results in a weaker quiet zone in the central region of the indoor window opening but a better quiet region along the indoor window opening periphery. This is somewhat expected. High frequency amplifications are still observed. The weak sound energy along the periphery and stronger sound energy within the central region of the indoor window opening give rise to similar sound reduction performances of the two control systems.

It is noted that $S_2$ appears in all higher-achieving clusters in this case of peripheral error microphone setting. Therefore, the use of dual clusters for further sound reduction performance improvement discussed in Sec. IV B 1 is not possible here. Apart from this issue, the performance of this peripheral error microphone system is comparable to that of the central error microphone system, in which the latter is only slightly better in terms of sound reduction

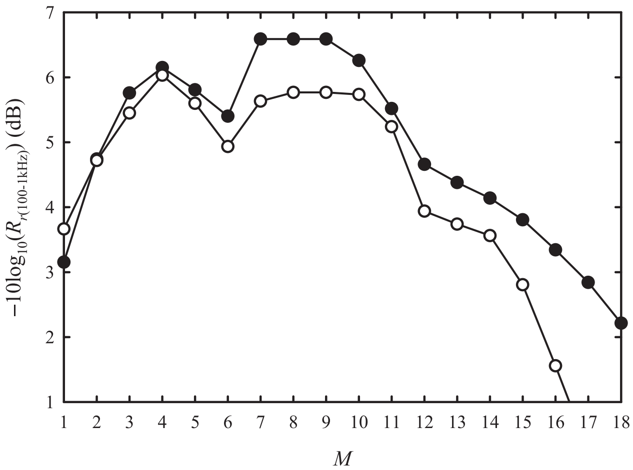


FIG. 8. Effect of the number of cancelling sources on sound reduction performance, with (●) error microphones $e_6$, $e_7$, $e_{10}$, $e_{11}$, $e_{14}$, $e_{15}$, and (○) error microphones $e_1$, $e_4$, $e_9$, $e_{12}$, $e_{17}$, $e_{20}$.

magnitude. However, the difference is well within engineering tolerance.

### 3. Reduced number of error microphones

Reducing the number of error microphones will certainly result in less sound energy reduction at the indoor window opening, lowering the effectiveness of sound cancellation. However, it is still worthwhile to understand what will happen when less complicated error microphone systems are adopted. Based on the above-presented results, the analysis is kept at $M \leq 4$ as more complicated cancelling source clusters are not preferred. Four simple error microphone settings are tested. They are $[e_1\ e_4\ e_9\ e_{12}]$, $[e_6\ e_7\ e_{10}\ e_{11}]$, $[e_1\ e_9\ e_{17}]$, and $[e_6\ e_{10}\ e_{14}]$. Cases with smaller $N$ are not discussed in the present study because it is expected that the corresponding active control will not be efficient.

Table III gives an overview of the performance of these four error microphone settings. At reduced $N$, there is an overall reduction in sound attenuation within the receiver room across the board with a maximum of just below 5 dB. The setting $[e_1\ e_4\ e_9\ e_{12}]$ can still result in some meaningful sound reductions, whereas the setting $[e_6\ e_{10}\ e_{14}]$ can only provide limited sound reduction when four cancelling sources are applied. One can expect the performance will be further worsened as $N$ is further reduced. Thus, the corresponding results are not presented. One can also infer, together with the results displayed in Tables I and II, that the sound reduction performance with a fixed $M$ will also decrease with a decreasing $N$. Although it is pointed out by Tan *et al.*[23] that the location of the error microphone does not have a significant impact on the active noise cancellation across their plenum window, there are many choices (or combinations of choices) of error microphone locations in the present plenum window. One can also observe that the sound spectra at these potential microphone locations can be very different (Fig. 5). The detailed effects on sound reduction performance as $N$ decreases when $M$ is fixed, which are important for creating a complete picture on the active cancellation performance, are left to further investigations. Again, it is observed that the cancelling sources near the indoor window opening are not helpful.

The foregoing analysis will discuss only the more meaningful control systems with overall sound reduction improvement over 4.5 dB. Figure 12(a) illustrates the spectral variations of sound energy ratio in the receiver room, $R_r$, achieved by the error microphone setting of $[e_1\ e_4\ e_9\ e_{12}]$ with different $M$. $R_r < 1$ represents sound attenuation. The focus is the frequency range from 100 to 1000 Hz. The corresponding result from the best performing cluster $[S_1\ S_2\ S_5\ S_8]$ under the error microphone setting of $[e_6\ e_7\ e_{10}\ e_{11}\ e_{14}\ e_{15}]$ is included in Fig. 12(a) for the sake of easy reference. One can observe that the low frequency $R_r$ between 100 Hz and around 160 Hz is slightly improved in the reduced $N$ cases, but the effective attenuation bandwidth is shortened, and the $R_r$ at higher frequencies is closer to unity (less attenuation) at the same time. This bandwidth appears narrower as $M$ decreases. One should note that the slightly lower attenuation at low frequencies in the $N = 6$ $[e_6\ e_7\ e_{10}\ e_{11}\ e_{14}\ e_{15}]$ case can be rectified by the dual cancelling source cluster method suggested in Sec. IV B 1.

Figure 12(b) shows the spectral sound attenuation of the best performing case under the error microphone setting of $[e_6\ e_{10}\ e_{14}]$. The low frequency performance, in this case, is still slightly better than that of the best $N = 6$ $[e_6\ e_7\ e_{10}\ e_{11}\ e_{14}\ e_{15}]$ case, but the effective bandwidth for sound attenuation is restricted to below 600 Hz, largely reducing the overall sound attenuation performance of this system.

TABLE I. Higher-achieving cancelling source clusters under central error microphone setting. Numbers in parenthesis, $-10\log_{10}(R_{r(100\text{-}1kHz)})$ in dB.

| | Higher-achieving clusters | | | |
|---|---|---|---|---|
| M | Best | Second best | Third best | Fourth best |
| 1 | $[S_{10}]$ (3.15) | $[S_2]$ (3.06) | $[S_{11}]$ (2.66) | $[S_9]$ (2.26) |
| 2 | $[S_2\ S_{10}]$ (4.73) | $[S_2\ S_{11}]$ (4.57) | $[S_1\ S_2]$ (4.51) | $[S_2\ S_9]$ (4.28) |
| 3 | $[S_1\ S_2\ S_4]$ (5.74) | $[S_2\ S_{10}\ S_{19}]$ (5.58) | $[S_1\ S_2\ S_5]$ (5.55) | $[S_2\ S_{10}\ S_{18}]$ (5.43) |
| 4 | $[S_2\ S_5\ S_{10}\ S_{18}]$ (6.15) | $[S_2\ S_6\ S_{10}\ S_{18}]$ (6.09) | $[S_1\ S_2\ S_5\ S_8]$ (5.99) | $[S_1\ S_2\ S_5\ S_{10}]$ (5.95) |
| 5 | $[S_1\ S_2\ S_5\ S_{10}\ S_{18}]$ (5.80) | $[S_1\ S_2\ S_5\ S_9\ S_{15}]$ (5.78) | $[S_1\ S_2\ S_5\ S_6\ S_{10}]$ (5.77) | $[S_1\ S_2\ S_5\ S_{10}\ S_{15}]$ (5.75) |
| 6 | $[S_1\ S_2\ S_5\ S_9\ S_{14}\ S_{15}]$ (5.39) | $[S_1\ S_2\ S_5\ S_9\ S_{12}\ S_{15}]$ (5.27) | $[S_1\ S_2\ S_5\ S_{10}\ S_{12}\ S_{15}]$ (5.15) | $[S_1\ S_2\ S_5\ S_8\ S_{13}\ S_{15}]$ (4.90) |
| 7 | $[S_1\ S_2\ S_5\ S_6\ S_9\ S_{15}\ S_{17}]$ (6.59) | $[S_1\ S_2\ S_5\ S_7\ S_9\ S_{14}\ S_{18}]$ (6.50) | $[S_1\ S_2\ S_5\ S_6\ S_9\ S_{14}\ S_{17}]$ (6.38) | $[S_1\ S_2\ S_5\ S_8\ S_9\ S_{14}\ S_{18}]$ (6.35) |
| 8 | $[S_1\ S_2\ S_5\ S_6\ S_8\ S_9\ S_{15}\ S_{17}]$ (6.59) | $[S_1\ S_2\ S_3\ S_5\ S_6\ S_9\ S_{15}\ S_{17}]$ (6.59) | $[S_1\ S_2\ S_5\ S_7\ S_8\ S_9\ S_{14}\ S_{18}]$ (6.50) | $[S_1\ S_2\ S_3\ S_5\ S_7\ S_9\ S_{14}\ S_{18}]$ (6.50) |

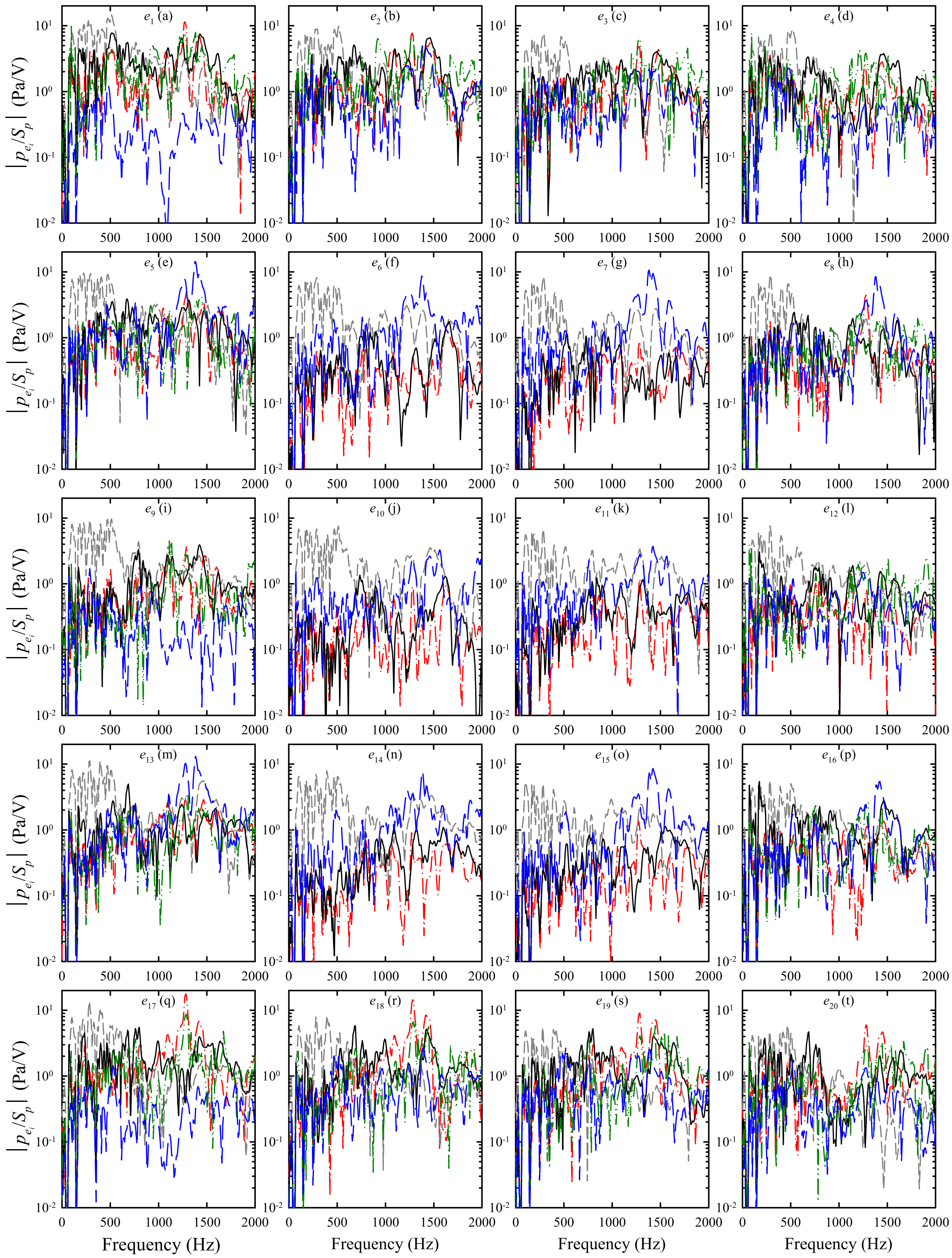

FIG. 9. (Color online) Spectral sound pressure distribution over indoor window exit in the presence of cancelling sources, showing (— — —) primary source alone; with error microphones $e_6$, $e_7$, $e_{10}$, $e_{11}$, $e_{14}$, $e_{15}$, (—) [$S_2$ $S_5$ $S_{10}$ $S_{18}$]; (— · —) [$S_1$ $S_2$ $S_5$ $S_8$]; (— ·· —) [$S_1$ $S_2$ $S_5$ $S_6$ $S_8$ $S_9$ $S_{15}$ $S_{17}$]; with error microphones $e_1$, $e_4$, $e_9$, $e_{12}$, $e_{17}$, $e_{20}$ (—–) [$S_1$ $S_2$ $S_5$ $S_9$].

For the sake of completeness, the overall spectral reductions of sound energy at the indoor window opening (represented by $R_e$) within the focused frequency range achieved by the above selected "error microphone-cancelling source" systems are given in Fig. 13. It is somewhat expected that the use of fewer error microphones leads to higher broadband sound levels at the indoor window opening and, thus, the observed less sound reduction inside the receiver room. The corresponding spectral sound pressure distributions over the indoor window opening are generally in line with

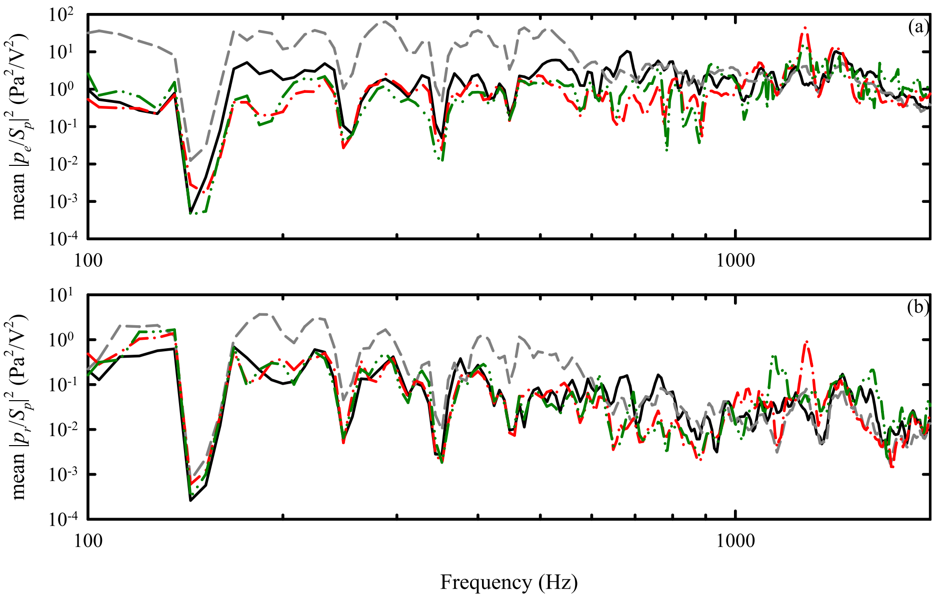


FIG. 10. (Color online) Additional information on bandwidths and averaged squared pressure over indoor window exit with error microphones, $e_6$, $e_7$, $e_{10}$, $e_{11}$, $e_{14}$, $e_{15}$. (a) Average squared pressure over indoor window exit; (– – –) primary source alone; (—) [$S_2$ $S_5$ $S_{10}$ $S_{18}$]; (— · —) [$S_1$ $S_2$ $S_5$ $S_8$]; (— ·· —) [$S_1$ $S_2$ $S_5$ $S_6$ $S_8$ $S_9$ $S_{15}$ $S_{17}$]; and (b) examples of receiver room sound reduction bandwidths, showing (– – –) primary source alone; (—) [$S_2$ $S_5$ $S_{10}$ $S_{18}$]; (— · —) [$S_1$ $S_2$ $S_5$ $S_8$]; (— ·· —) [$S_1$ $S_2$ $S_5$ $S_{10}$ $S_{18}$].

those presented in Fig. 9 with six error microphones. Therefore, they are not presented.

One can conclude from Figs. 12 and 13 that the use of fewer error microphones does reduce the effectiveness of the active reduction of sound transmission across the plenum window. However, the simplified systems with four error microphones can still provide reasonable sound attenuation and, thus, could be useful when the required additional sound reduction is around 5 dB at frequencies below 1000 Hz. The simplicity makes these systems viable for practical implementation.

## V. CONCLUSIONS

An experimental study is performed in the present investigation to understand how the different combinations of secondary cancelling sources and error microphones will affect the possible active cancellation of sound transmission across a practical plenum window with relatively large openings, a short overlapping length, and a narrow gap between glass panes. The error microphones were mounted at the indoor window opening, whereas the cancelling sources were located on the internal periphery of the plenum window void. The analysis was completed using measured transfer functions along all sound transmission paths. The number of error microphones in a control system was limited to six because any complicated system is not desirable for practical implementation.

The present results suggest that the number of secondary cancelling sources should be kept below eight as more sources will not give meaningful further sound reduction in the receiver room. In general, cancelling sources located near the window corners at the outdoor window opening and within the overlapping region of the window void play more important roles in the active control process. Also, it is observed that the control system can attenuate sound between 100 and ~1000 Hz. The ineffectiveness at higher frequencies is a result of the strong sound reduction capacity of the plenum window itself.

For the case with six error microphones in the central region of the indoor window opening, it is found that four cancelling sources, located around the outdoor opening of the window, are already enough in terms of system complexity, sound reduction level, and the bandwidth of the



TABLE II. Higher-achieving cancelling source clusters under peripheral error microphone setting. Numbers in parenthesis, $-10\log_{10}(R_{r(100\text{-}1\text{kHz})})$ in dB.

| | Higher-achieving clusters | | | |
|---|---|---|---|---|
| $M$ | Best | Second best | Third best | Fourth best |
| 1 | [$S_2$] (3.66) | [$S_1$] (2.47) | [$S_4$] (0.60) | [$S_8$] (0.50) |
| 2 | [$S_1$ $S_2$] (4.72) | [$S_2$ $S_8$] (4.63) | [$S_2$ $S_9$] (4.38) | [$S_2$ $S_{10}$] (4.37) |
| 3 | [$S_1$ $S_2$ $S_8$] (5.45) | [$S_1$ $S_2$ $S_{10}$] (5.37) | [$S_1$ $S_2$ $S_4$] (5.33) | [$S_1$ $S_2$ $S_5$] (5.31) |
| 4 | [$S_1$ $S_2$ $S_5$ $S_9$] (6.03) | [$S_1$ $S_2$ $S_5$ $S_{10}$] (5.88) | [$S_1$ $S_2$ $S_6$ $S_9$] (5.77) | [$S_1$ $S_2$ $S_5$ $S_8$] (5.66) |
| 5 | [$S_1$ $S_2$ $S_5$ $S_{10}$ $S_{13}$] (5.60) | [$S_1$ $S_2$ $S_5$ $S_{10}$ $S_{19}$] (5.58) | [$S_1$ $S_2$ $S_5$ $S_{10}$ $S_{12}$] (5.55) | [$S_1$ $S_2$ $S_4$ $S_{10}$ $S_{12}$] (5.48) |
| 6 | [$S_1$ $S_2$ $S_5$ $S_9$ $S_{10}$ $S_{18}$] (4.94) | [$S_1$ $S_2$ $S_5$ $S_9$ $S_{10}$ $S_{19}$] (4.72) | [$S_1$ $S_2$ $S_7$ $S_9$ $S_{10}$ $S_{13}$] (4.70) | [$S_1$ $S_2$ $S_4$ $S_9$ $S_{10}$ $S_{19}$] (4.56) |
| 7 | [$S_1$ $S_2$ $S_5$ $S_6$ $S_9$ $S_{10}$ $S_{13}$] (5.63) | [$S_1$ $S_2$ $S_5$ $S_6$ $S_9$ $S_{15}$ $S_{17}$] (5.45) | [$S_1$ $S_2$ $S_5$ $S_6$ $S_9$ $S_{10}$ $S_{14}$] (5.44) | [$S_1$ $S_2$ $S_5$ $S_6$ $S_9$ $S_{10}$ $S_{15}$] (5.43) |
| 8 | [$S_1$ $S_2$ $S_5$ $S_6$ $S_8$ $S_9$ $S_{10}$ $S_{13}$] (5.77) | [$S_1$ $S_2$ $S_4$ $S_5$ $S_6$ $S_9$ $S_{10}$ $S_{13}$] (5.73) | [$S_1$ $S_2$ $S_3$ $S_5$ $S_6$ $S_9$ $S_{10}$ $S_{13}$] (5.63) | [$S_1$ $S_2$ $S_5$ $S_6$ $S_8$ $S_9$ $S_{10}$ $S_{15}$] (5.48) |

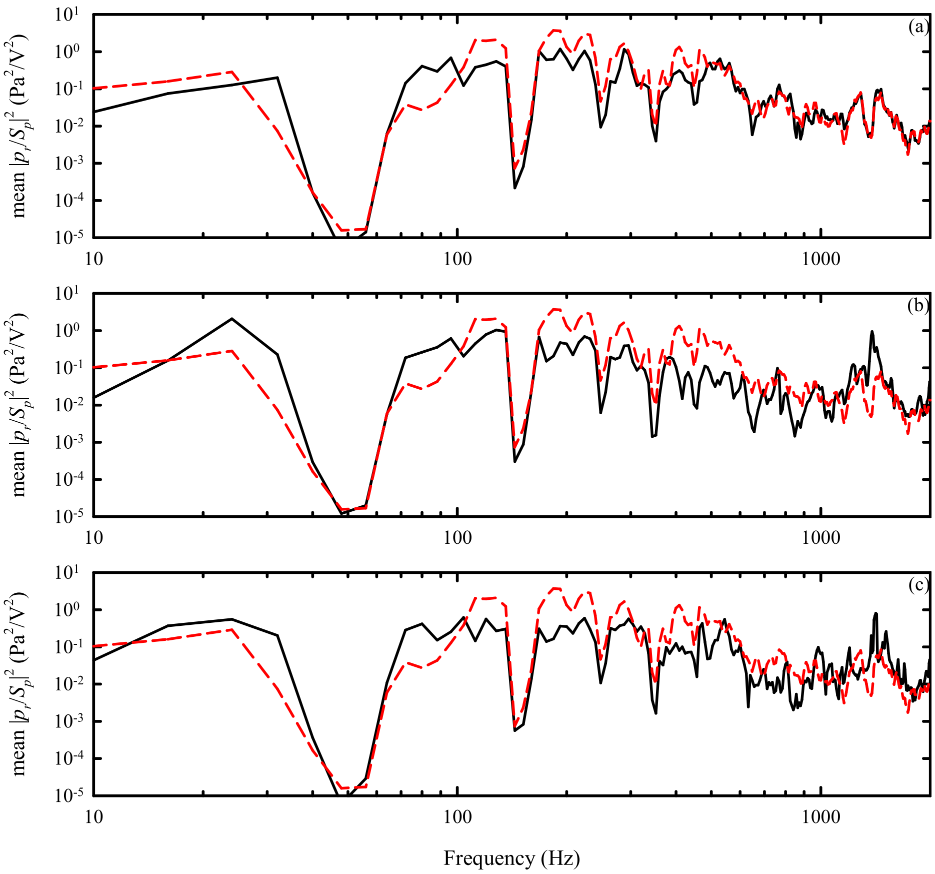


FIG. 11. (Color online) Spectral characteristics of sound reduction due to cancelling source clusters. Error microphones, $e_1$, $e_4$, $e_9$, $e_{12}$, $e_{17}$, $e_{20}$. (a) [$S_2$]; (b) [$S_1$ $S_2$ $S_5$ $S_9$]; (c) [$S_1$ $S_2$ $S_5$ $S_6$ $S_8$ $S_9$ $S_{10}$ $S_{13}$]. (—) Cancelling sources ON; (– – –) without cancelling sources.



reduction. Such a setup also allows a dual control system, consisting of two independent cancelling source clusters to be adopted, with one looking after the low frequency attenuation around 100 Hz and the other for higher frequencies below 1000 Hz. More cancelling sources will create a stronger quiet zone in the centre of the indoor window opening but does not produce meaningful further sound reduction despite the complexity of the system. The maximum achievable sound reduction within the frequency range from 100 to 1000 Hz is around 6 dB.

A similar sound reduction of 6 dB is observed when the six error microphones are equally spaced along the periphery of the indoor window opening. In this case, the best performing cancelling source cluster consists of four members, which are

TABLE III. Higher-achieving cancelling source clusters at reduced $N$. Numbers in parenthesis, $-10\log_{10}(R_{r(100\text{-}1\text{kHz})})$ in dB.

| Error microphone setting | $M$ | Higher-achieving clusters | | | |
|---|---|---|---|---|---|
| | | Best | Second best | Third best | Fourth best |
| [$e_1$ $e_4$ $e_9$ $e_{12}$] | 1 | [$S_2$] (1.03) | [$S_1$] (0.81) | [$S_8$] (0.61) | [$S_7$] (0.43) |
| | 2 | [$S_1$ $S_2$] (4.63) | [$S_2$ $S_{10}$] (3.83) | [$S_1$ $S_{10}$] (3.28) | [$S_2$ $S_{11}$] (3.19) |
| | 3 | [$S_1$ $S_2$ $S_{10}$] (4.98) | [$S_2$ $S_9$ $S_{10}$] (4.65) | [$S_1$ $S_2$ $S_{11}$] (4.21) | [$S_1$ $S_2$ $S_{16}$] (4.09) |
| | 4 | [$S_1$ $S_2$ $S_9$ $S_{10}$] (4.95) | [$S_1$ $S_2$ $S_{10}$ $S_{15}$] (4.05) | [$S_1$ $S_2$ $S_{11}$ $S_{15}$] (3.64) | [$S_1$ $S_2$ $S_{10}$ $S_{14}$] (3.61) |
| [$e_6$ $e_7$ $e_{10}$ $e_{11}$] | 1 | [$S_{10}$] (2.38) | [$S_{11}$] (2.02) | [$S_9$] (1.76) | [$S_{12}$] (1.70) |
| | 2 | [$S_1$ $S_2$] (3.83) | [$S_2$ $S_{11}$] (3.64) | [$S_2$ $S_{10}$] (3.61) | [$S_2$ $S_{12}$] (3.02) |
| | 3 | [$S_2$ $S_6$ $S_{11}$] (4.36) | [$S_2$ $S_5$ $S_{11}$] (4.08) | [$S_1$ $S_2$ $S_{10}$] (4.05) | [$S_2$ $S_5$ $S_{10}$] (3.93) |
| | 4 | [$S_2$ $S_{11}$ $S_{15}$ $S_{18}$] (2.71) | [$S_2$ $S_{11}$ $S_{14}$ $S_{18}$] (2.57) | [$S_2$ $S_{12}$ $S_{15}$ $S_{18}$] (2.45) | [$S_2$ $S_{10}$ $S_{16}$ $S_{17}$] (2.44) |
| [$e_1$ $e_9$ $e_{17}$] | 1 | [$S_2$] (3.65) | [$S_1$] (2.10) | [$S_{11}$] (0.14) | [$S_5$] (0.06) |
| | 2 | [$S_2$ $S_{11}$] (3.56) | [$S_2$ $S_{10}$] (3.46) | [$S_1$ $S_{11}$] (3.44) | [$S_1$ $S_{10}$] (3.14) |
| | 3 | [$S_2$ $S_5$ $S_{10}$] (2.69) | [$S_2$ $S_9$ $S_{10}$] (2.50) | [$S_2$ $S_5$ $S_{11}$] (2.34) | [$S_2$ $S_4$ $S_9$] (2.15) |
| | 4 | [$S_2$ $S_5$ $S_7$ $S_9$] (3.49) | [$S_2$ $S_4$ $S_5$ $S_9$] (3.21) | [$S_2$ $S_4$ $S_9$ $S_{10}$] (3.16) | [$S_2$ $S_4$ $S_7$ $S_9$] (2.88) |
| [$e_6$ $e_{10}$ $e_{14}$] | 1 | [$S_2$] (3.01) | [$S_{10}$] (2.97) | [$S_{11}$] (2.58) | [$S_{12}$] (2.05) |
| | 2 | [$S_2$ $S_{11}$] (4.25) | [$S_2$ $S_{10}$] (4.22) | [$S_2$ $S_{12}$] (3.78) | [$S_2$ $S_9$] (3.70) |
| | 3 | [$S_1$ $S_2$ $S_5$] (2.63) | [$S_2$ $S_5$ $S_9$] (2.22) | [$S_1$ $S_2$ $S_4$] (1.88) | [$S_2$ $S_6$ $S_9$] (1.80) |
| | 4 | [$S_1$ $S_2$ $S_5$ $S_6$] (4.70) | [$S_2$ $S_5$ $S_6$ $S_9$] (3.80) | [$S_2$ $S_4$ $S_5$ $S_9$] (3.55) | [$S_2$ $S_5$ $S_7$ $S_9$] (3.52) |

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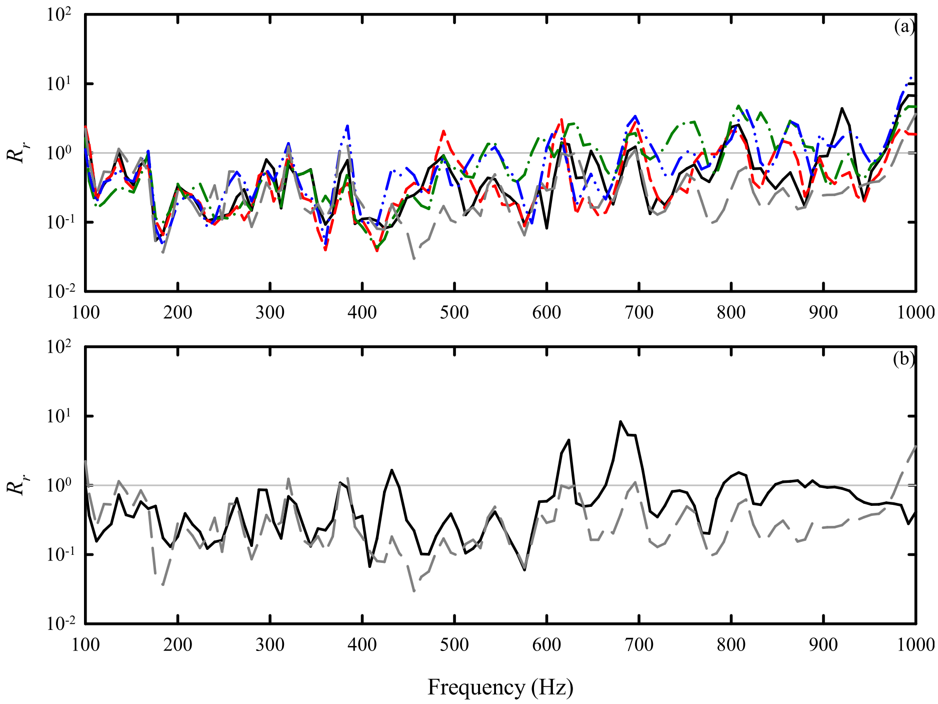


FIG. 12. (Color online) Spectral variations of sound reduction inside receiver rooms at reduced number of error microphones, showing (a) [$e_1$ $e_4$ $e_9$ $e_{12}$] (—) [$S_1$ $S_2$ $S_9$ $S_{10}$]; (– – –) [$S_1$ $S_2$ $S_{10}$]; (— · —) [$S_2$ $S_9$ $S_{10}$]; (— ·· —) [$S_1$ $S_2$]; (— — —) [$S_1$ $S_2$ $S_5$ $S_8$] under [$e_6$ $e_7$ $e_{10}$ $e_{11}$ $e_{14}$ $e_{15}$]; and (b) [$e_6$, $e_{10}$, $e_{14}$] (—) [$S_1$ $S_2$ $S_5$ $S_6$]; (— — —) [$S_1$ $S_2$ $S_5$ $S_8$] under [$e_6$ $e_7$ $e_{10}$ $e_{11}$ $e_{14}$ $e_{15}$].

very similar to those observed in the central error microphone case. However, the abovementioned plausible dual system setup cannot be implemented such that the low frequency performance for this error microphone setting will be inferior to that of the dual control system mentioned above.

The overall sound reduction inside the receiver room continues to decrease when fewer error microphones are used. For systems with four error microphones located in the centre or at the periphery of the indoor window opening, the maximum observed sound reduction between 100 and 1000 Hz is around 5 dB. Such a number falls to ∼4 dB when three error microphones located on a vertical column at the periphery or in the centre of the indoor window opening are used.



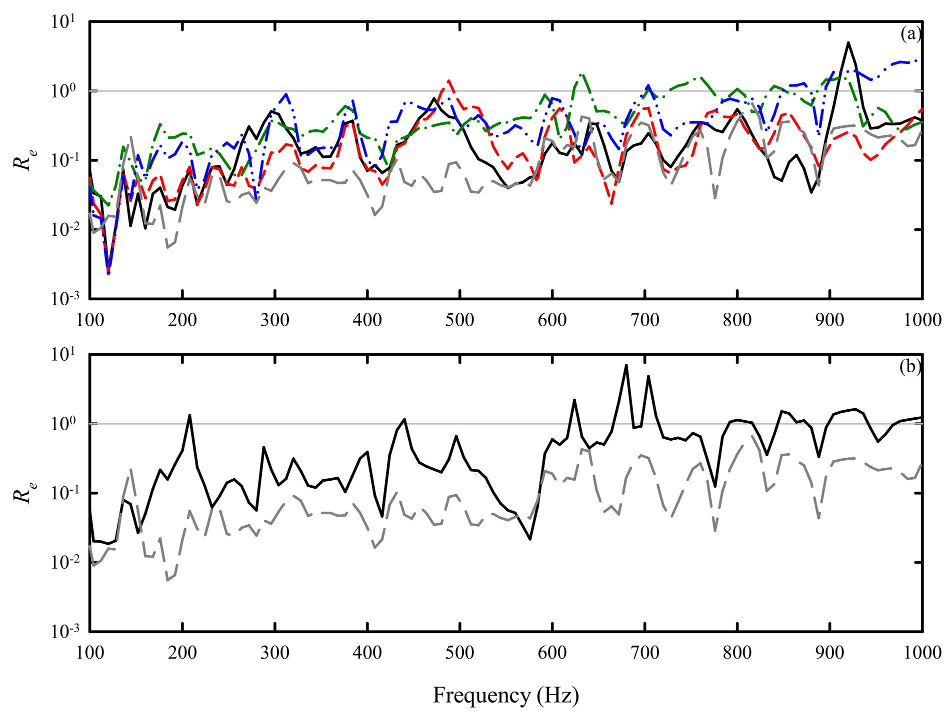


FIG. 13. (Color online) Spectral variations of sound reduction over indoor window exit at reduced number of error microphones, showing (a) [$e_1$ $e_4$ $e_9$ $e_{12}$] (—) [$S_1$ $S_2$ $S_9$ $S_{10}$]; (– – –) [$S_1$ $S_2$ $S_{10}$]; (— · —) [$S_2$ $S_9$ $S_{10}$]; (— ·· —) [$S_1$ $S_2$]; (— — —) [$S_1$ $S_2$ $S_5$ $S_8$] under [$e_6$ $e_7$ $e_{10}$ $e_{11}$ $e_{14}$ $e_{15}$]; and (b) [$e_6$, $e_{10}$, $e_{14}$] (—) [$S_1$ $S_2$ $S_5$ $S_6$]; (— — —) [$S_1$ $S_2$ $S_5$ $S_8$] under [$e_6$ $e_7$ $e_{10}$ $e_{11}$ $e_{14}$ $e_{15}$].

## ACKNOWLEDGMENTS

The present study is funded by Environment and Conservation Fund, Hong Kong under Grant No. ECF92/2020.

## AUTHOR DECLARATIONS

### Conflict of Interest

The authors have no conflicts to disclose.

## DATA AVAILABILITY

The data that support the findings of this study are available from the corresponding author upon reasonable request.

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