PAN
ARCHIVES OF ACOUSTICS
Vol. **43**, No. 4, pp. 739–746 (2018)
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DOI: 10.24425/aoa.2018.125167

Technical Note

Incorporation of Resonators Into Plenum Window

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(*received May 26, 2018; accepted July 30, 2018*)

A plenum window with incorporation of Helmholtz resonators in between two glass panes was tested in a reverberation room. The effects of jagged flap on reducing strength of diffracted sound was also investigated in the present studies where white, traffic and construction noises were examined during each set of experiment. When the noise source was located at the central line of the plenum window, the plenum window with Helmholtz resonators was able to mitigate 8.5 dBA, 8.9 dBA and 8.2 dBA of white, traffic and construction noises, respectively, compared with the case of without window. These amounts of noises that attenuated by the plenum window were slightly higher than the case where noise source was diverged 30° away from the plenum window. The effects of jagged flaps on the acoustical performance of the plenum window were negligible. The Helmholtz resonators had the best performance in the frequency region between 900 Hz to 1300 Hz where in this frequency range, the plenum window with Helmholtz resonators was able to attenuate additional 1.7 dBA, 1.9 dBA and 1.6 dBA of white, traffic and construction noises, respectively, compared with the case of without resonators.

Keywords: plenum window; Helmholtz resonators; noise pollution; ventilation.
Subject classification code: T210 (CERIF).

Notations

- c – speed of sound in air,
- f_r – resonance frequency,
- L_{Aeq} – equivalent sound pressure level,
- ΔL_{Aeq} – reduction of equivalent sound pressure level,
- n – length of neck,
- S – cross sectional area of the resonator opening,
- V – volume of the resonator,
- σ – slit size.

1. Introduction

As the world becomes more urbanized, the use of machine-technology increases such as motor vehicles and construction machines and thus, the chances of human exposure to noise are increased. Noise annoys people, disrupts communication and individual thoughts and the combination of these numerous effects of noise will detract the quality of people's lives. Two methods which commonly used by community nowadays to solve the noise pollution issue are noise barrier (Palma, Samagaio, 2006; Chen *et al.*, 2011) and sound absorption materials (Liu *et al.*, 2014; Zhu *et al.*, 2016). Noise barrier normally is used to block an outdoor door noise from propagates directly from the noise source to the residential area. Sound absorption materials normally are used to absorb an indoor noise to minimize the amount of noise from propagates to the surrounding area. Indoor noise is easily to be reduced to a very low level due to the blockage of the building walls and also absorption of the sound material. However for outdoor noise, the noise still reaches the receiver by few ways even with the blockage of the noise barrier (Menounou, Busch-Vishniac, 2000). First, through the diffraction over the top edge and around the side edges of the barrier. Second, through reflections from other structures. Third, through scattering from turbulence in the air and finally through refraction due to wind and temperature changes. Thus, the idea of this study is to develop a type of sound attenuation device where can protect the residents from the disturbance of the outdoor noises which majorally are composed of traffic and construction noises.

Ford and Kerry (1973) defined plenum window as a partially opened double glazing window. The inner and outer window openings are staggered and thus, noise cannot directly propagate across it. In addition, the gap between the two glass panes together with the opening form an air passage which allows outdoor air to ventilate the indoor space. Sondergaard and Olesen (2011) studied the sound insulation properties of a supply air window which consisted of top and bottom hung vents in the outer and inner parts of the window, respectively. The supply air window was found to be able to obtain 8 dB to 16 dB of sound insulation. Tong and Tang (2013) studied the acoustical insertion loss (IL) of a 1:4 scaled down plenum window installed on a building facade in the presence of a non-parallel line source in a semi-anechoic chamber. For the case where orientation of the building facade relative to the line source was allowed to change, the maximum and minimum IL were found to be around 18 dB and 8 dB, respectively. Tong *et al.* (2015) carried out a full scale field measurement of the acoustical IL of a plenum window. They concluded the acoustical benefit achieved by replacing side-hung casement window with the plenum window tested in their study was between 7.1 dBA and 9.5 dBA. A series of experiments was conducted by Tang *et al.* (2016) in an attempt to understand how the implementation of active noise control would affect the sound transmission across a plenum window. They found that the active control system with two loudspeakers located symmetrically about the plenum cavity horizontal centerline facing directly the incoming noise gave the best performance. Tong and Tang (2017) investigated the acoustical performance of a full-scale plenum window with total of 24 different configurations of opening sizes, gap widths and overlapping lengths with and without sound absorption materials. They concluded that maximum 19 dBA and 15 dBA of transmission and insertion losses were achieved by the plenum window, respectively.

Helmholtz resonator (HR) is a well known device which consists of a cavity communicating with an external duct through an orifice. It can be used to reduce noise centralized at its resonance frequency. HR has been utilized in numerous applications for sound attenuation such as aero-engines, building and automotive systems due to its simple and tunable characteristics. Wu and Zhang (2017) used the planar wave theory and the transfer matrix method to investigate wave propagation in the duct-resonator system. Their theoretical results indicated that both the periodic duct-resonator and the modified duct-resonator systems could broaden the noise attenuation band. Hu *et al.* (2018) investigated the tuning of an acoustic resonator, in terms of its Helmholtz frequency and the internal resistance for the control of a narrowband noise in an acoustic enclosure. Their numerical study results showed the possibility of using mistuned resonators to maximize the noise reduction, as well as the tuning level required for different narrow frequency bands of interests. Zhu *et al.* (2018) installed a lightweight membrane-type resonator in the back cavity of the perforated panel to combine into a compound sound absorber in order to broaden the sound absorption bandwidth of a perforated panel in the low frequency range. They obtained a wide frequency band having a large sound absorption coefficient by tuning the parameters of the membrane type resonator. Cai and Mak (2018) investigated the wave propagation in a duct mounted with a periodic dual HR array theoretically and numerically. They concluded that periodic dual array could provide much broader noise attenuation bands at the designed resonance frequencies of the dual HR.

From reported works, it can be seen that the plenum window is an effective structure to mitigate outdoor noise while maintaining good ventilation of the indoor space. In addition, it can be directly installed at the window frame of the building and thus, it requires much smaller installation space compared to noise barrier in order to provide same level of noise attenuation effect. However, plenum window is not able to attenuate noise based on certain targeted frequency range. Therefore, several resonators were incorporated into the plenum window in the present studies in order to mitigate noise at lower frequency range as traffic and construction noises are normally centralized at frequencies around 1000 Hz.

2. Experimental set-up

The plenum window with rectangular HRs were fabricated and were tested in a reverberation room as shown in Fig. 1a. The receiver room is qualified for the frequency range from 100 Hz to 5000 Hz based on ASTM E2235. The HRs were made by acrylic because acrylic is easy to be fabricated and it is transparent. Three rectangular resonators were installed at the central of the plenum window because according to Wu and Zhang (2017), combining several resonators in line is a possible way to produce a broader noise attenuation band. The geometry of the resonator (see Fig. 1d) was expected to produce resonance fre-

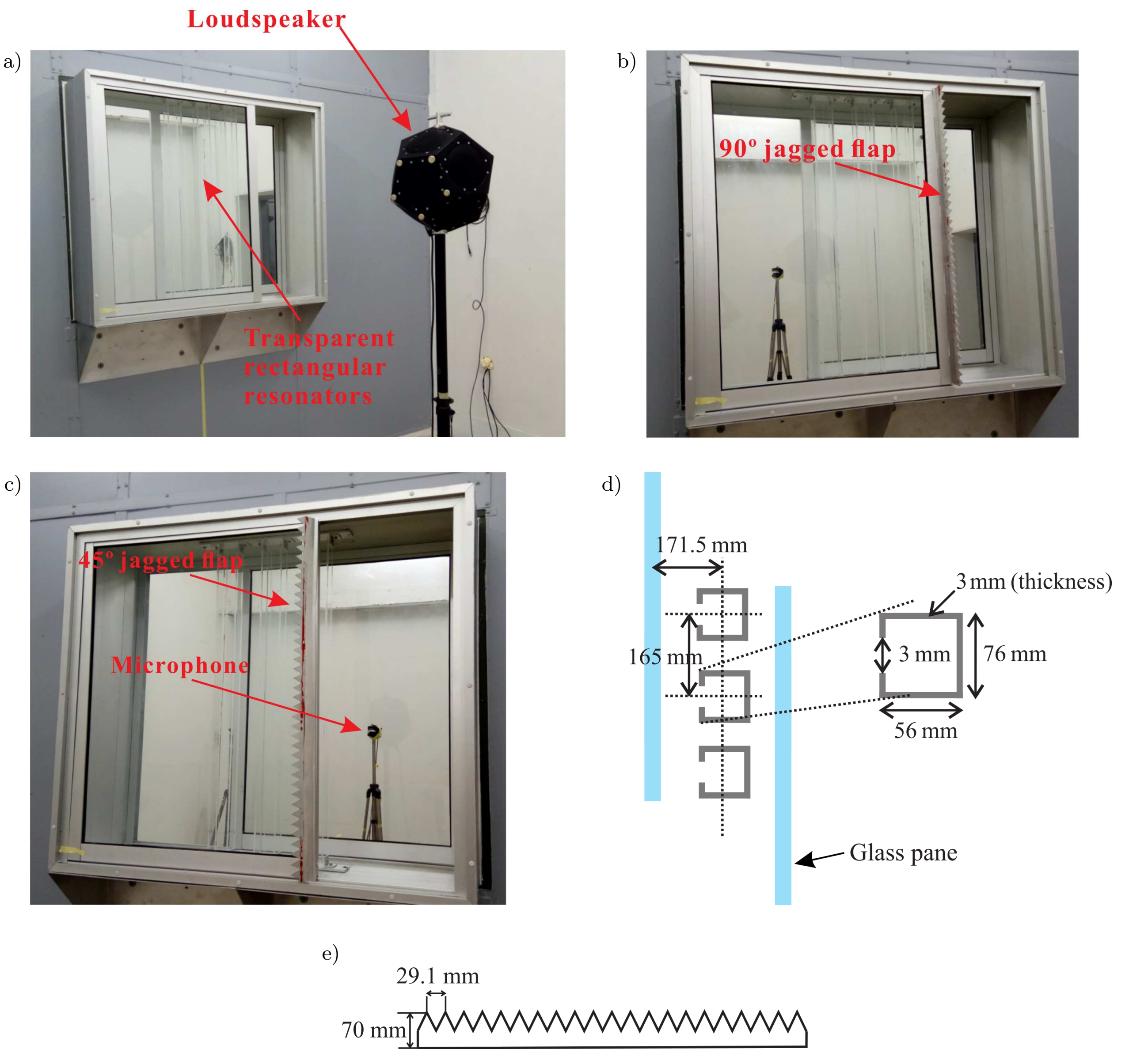

Fig. 1. a) Experimental set-up of the plenum window with rectangular HRs at reverberation room, b) plenum window with attached 90° jagged flap, c) plenum window with attached 45° jagged flap, d) geometry of the plenum window with HRs (top view), e) geometry of the jagged flap.

quency (f_r) of 676 Hz based on Eq. (1) (Everest, Pohlmann, 2009):

$$f_r = \frac{c}{2\pi}\sqrt{\frac{S}{V(n+0.9\sigma)}}, \tag{1}$$

where c is the speed of sound in air, S is the cross sectional area of the resonator opening, V is the volume of the resonator, n is the length of neck and σ is the slit size. The measuring equipment consisted of a Bruel & Kjaer (B&K) power amplifier (model 2734-A), a SONY boombox (model ZR-RS70BT), a Larson Davis Omnisource loudspeaker (model BAS001) and a PCB Piezotronics microphone (model 377B02). White, traffic and construction noises were played using the SONY boombox while loudspeaker and amplifier were used to make those noises propagated in omni direction and to amplify the volume of those noises, respectively. Two types of experiments were conducted in the reverberation room with different locations of noise source. For experiment A, the microphone and loudspeaker were placed at central line of the plenum window and also central of the reverberation room as shown in Fig. 2. For experiment B, the loudspeaker was diverged 30° away from its original position in experiment A in order to investigate the effect of noise source position on the noise attenuation performance of the plenum window.

For both experiments A and B, a jagged flap was attached perpendicularly (90°) to the edge of the plenum

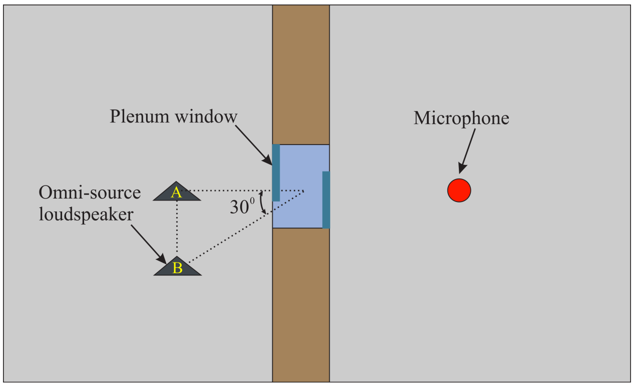

Fig. 2. Schematic diagram of the experimental set-up for experiments A and B.

window glass pane (see Fig. 1b) in order to reduce the strength of diffracted sound because sound diffraction might be occurred over the edge of the glass pane or gap between the two glass panes. The effects of the jagged flap angle on the acoustical performance of the plenum window was also investigated in the present studies by bending the jagged flap about 45° as shown in Fig. c. The geometry of the jagged flap is shown in Fig. 1e. All data were recorded using microphone from 100 Hz to 5000 Hz with interval of 2 Hz where three samples were recorded and were averaged for each data set. The sampling time for each sample is 45 s and all recorded data were analysed using B&K Sonoscout software. Sound pressure levels (SPLs) for experiment without plenum window were also measured in order to obtain IL_1 based on Eq. (2). Without plenum window means when there is nothing in the wall opening. The case of without plenum window is actually similar to the case of fully opened window for those conventional glass windows where their glass panes can be fully pushed to outside. Thus, the whole structure was directly compared with the case of without plenum window in order to save the cost and time of installing conventional window in the reverberation room. In addition, IL_2 which computed the differences of SPLs between cases of with and without HRs was obtained using Eq. (3). The equivalent SPL (L_{Aeq}) and reduction of L_{Aeq} (ΔL_{Aeq}) were also obtained for all experiments based on Eqs. (4), (5) and (6)

$$\begin{aligned}\mathrm{IL}_1 = {} & \mathrm{SPL}_{\text{without window}} \\ & - \mathrm{SPL}_{\text{with window and resonators}},\end{aligned} \tag{2}$$

$$\begin{aligned}\mathrm{IL}_2 = {} & \mathrm{SPL}_{\text{window without resonators}} \\ & - \mathrm{SPL}_{\text{window with resonators}},\end{aligned} \tag{3}$$

$$L_{\mathrm{Aeq}} = 10\log\left(\sum_{i=1}^{n} t_i 10^{\left(\frac{\mathrm{SPL}_i}{10}\right)}\right), \tag{4}$$

where i and n represent the first and last SPLs in the measured frequency range, respectively, t_i is the fraction of the time period that the noise has a sound level of SPL_i

$$\begin{aligned}\Delta L_{\mathrm{Aeq1}} = {} & L_{\mathrm{Aeq\ (without\ window)}} \\ & - L_{\mathrm{Aeq\ (with\ window\ and\ resonators)}}.\end{aligned} \tag{5}$$

$$\begin{aligned}\Delta L_{\mathrm{Aeq2}} = {} & L_{\mathrm{Aeq\ (window\ without\ resonators)}} \\ & - L_{\mathrm{Aeq\ (window\ with\ resonators)}}.\end{aligned} \tag{6}$$

3. Results and discussion

Table 1 shows the noise reduction obtained by the plenum window with HRs when comparing with the case of without plenum window at frequencies ranging from 100 Hz to 5000 Hz. For experiment A, plenum window with HRs is able to attenuate 8.5 dBA, 8.9 dBA and 8.2 dBA of white, traffic and construction noises, respectively. When the noise source is diverged 30° away from the plenum window (experiment B), the plenum window is able to attenuate 7.8 dBA, 8.0 dBA and 7.5 dBA of white, traffic and construction noises, respectively. Even the data in the present studies are measured in a reverberation room, it is found that when the noise source is located at the central line of the plenum window, the amount of noise that mitigated by the plenum window is higher than the case where noise source is diverged 30° away from the central line of the plenum window. This phenomenon might be due to the condition where for experiment A, some of the noises are directly reflected back by the glass pane. However for experiment B, some of the noises might be directly propagating through the opening of the plenum window before they have chance to be reflected by the glass pane or the wall of the reverberation room. It is found from Table 1 that the effects of both 90° and 45° jagged flaps on the acoustical performance of the plenum window are negligible for all noises and for both experiments. These results might be due to: first, only little occurrence of noise

Table 1. ΔL_{Aeq1} [dBA] for experiments A and B when frequencies are ranging from 100 Hz to 5000 Hz. W, T and C represent white, traffic and construction noises, respectively.

Experiment	A (W)	B (W)	A (T)	B (T)	A (C)	B (C)
Without jagged flap	8.5	7.8	8.9	8.0	8.2	7.5
With 90° jagged flap	8.4	7.8	8.8	8.1	8.4	7.8
With 45° jagged flap	8.3	7.6	8.7	7.9	8.3	7.7

diffraction because the gap between two glass panes is around 0.34 m and the edge of the glass pane is around 1.08 m which means only noise with frequencies lower than 1000 Hz and 316 Hz might be diffracted over the gap and edge, respectively. Second, the geometry of the jagged flap is not optimised yet such that further study should be conducted to optimise various design parameters of the jagged flap such as height, angle and length of the jagged segment.

Figure 3 shows the IL_2 obtained by the plenum window with HRs when comparing with the case of without resonators. Generally for all three noises, there is no significant difference of the IL trends between experiments A and B. For both experiments and for all three noises, their IL keep fluctuating over the whole frequency range except in the frequencies between 1400 Hz and 1600 Hz where in this region, their IL exhibit a great amount of decrement. For experiment A, at frequency of 690 Hz (data is measured but not shown in Fig. 3) which is very near to the targeted f_r (676 Hz), the plenum window with HRs is able to mitigate additional 6.7 dBA, 8.6 dBA and 7.9 dBA of white, traffic and construction noises, respectively, compared to case of without resonators. It is found that the resonators have the best performance in the frequency region between 900 Hz to 1300 Hz and thus, the additional noise reduction obtained by the resonators at this region is shown in Table 2. This frequency region is slightly higher than the f_r that estimated in the current studies due the theory of Helmholtz resonance where the theory assumes that the noise propagates directly to the direction of resonators and there is no obstacle in between source and receiver. However in current experiments, the glass pane which located in front of the resonators blocks the direct propagation of noise

a) b) c)

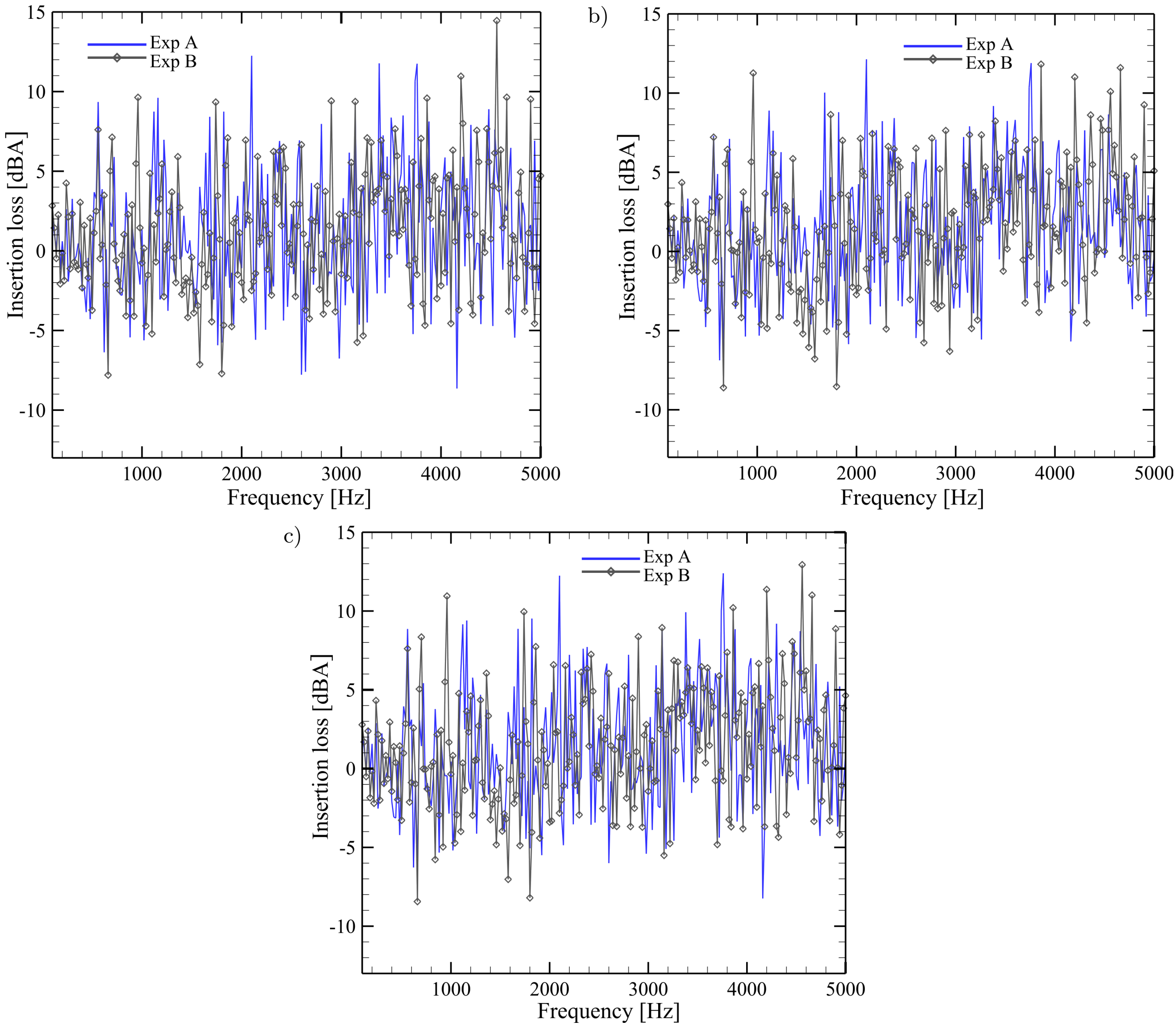

Fig. 3. IL_2 obtained by the plenum window with HRs (without jagged flap) when comparing with the case of without resonators for experiments A and B: a) white noise, b) traffic noise, c) construction noise (the data are recorded at interval of 2 Hz, but the results are presented at interval of 20 Hz for clearer presentation of the IL trends).

Table 2. ΔL_{Aeq2} [dBA] for experiments A and B when frequencies are ranging from 900 Hz to 1300 Hz. W, T and C represent white, traffic and construction noises, respectively.

Experiment	A (W)	B (W)	A (T)	B (T)	A (C)	B (C)
Without jagged flap	1.7	1.5	1.9	1.4	1.6	1.9
With 90° jagged flap	1.6	1.4	1.7	1.1	1.4	1.4
With 45° jagged flap	1.6	1.2	1.7	0.9	1.4	1.3

from source to the receiver. It is observed from Table 2 that for experiment A, the plenum window with HRs is able to attenuate additional 1.7 dBA, 1.9 dBA and 1.6 dBA of white, traffic and construction noises, respectively, compared to the case of without resonators. Similar to the results that obtained for wide frequency range (see Table 1), the effects of jagged flaps on the noise attenuation performance of the plenum window at this narrow frequency region are also negligible for all three noises and for both experiments. It also can be observed from Table 2 that the overall noise reduction that obtained from experiment A for all three noises are higher or similar to that from experiment B except for construction noise for the case of without jagged flap. This result might be due to the high IL_2 that obtained from experiment B at 960 Hz which is about 10.9 dBA (see Fig. 3c). The IL_2 obtained by the plenum window with HRs (attached 90° and 45° jagged flaps) when comparing with the case of without resonators are shown in Figs. 4 and 5.

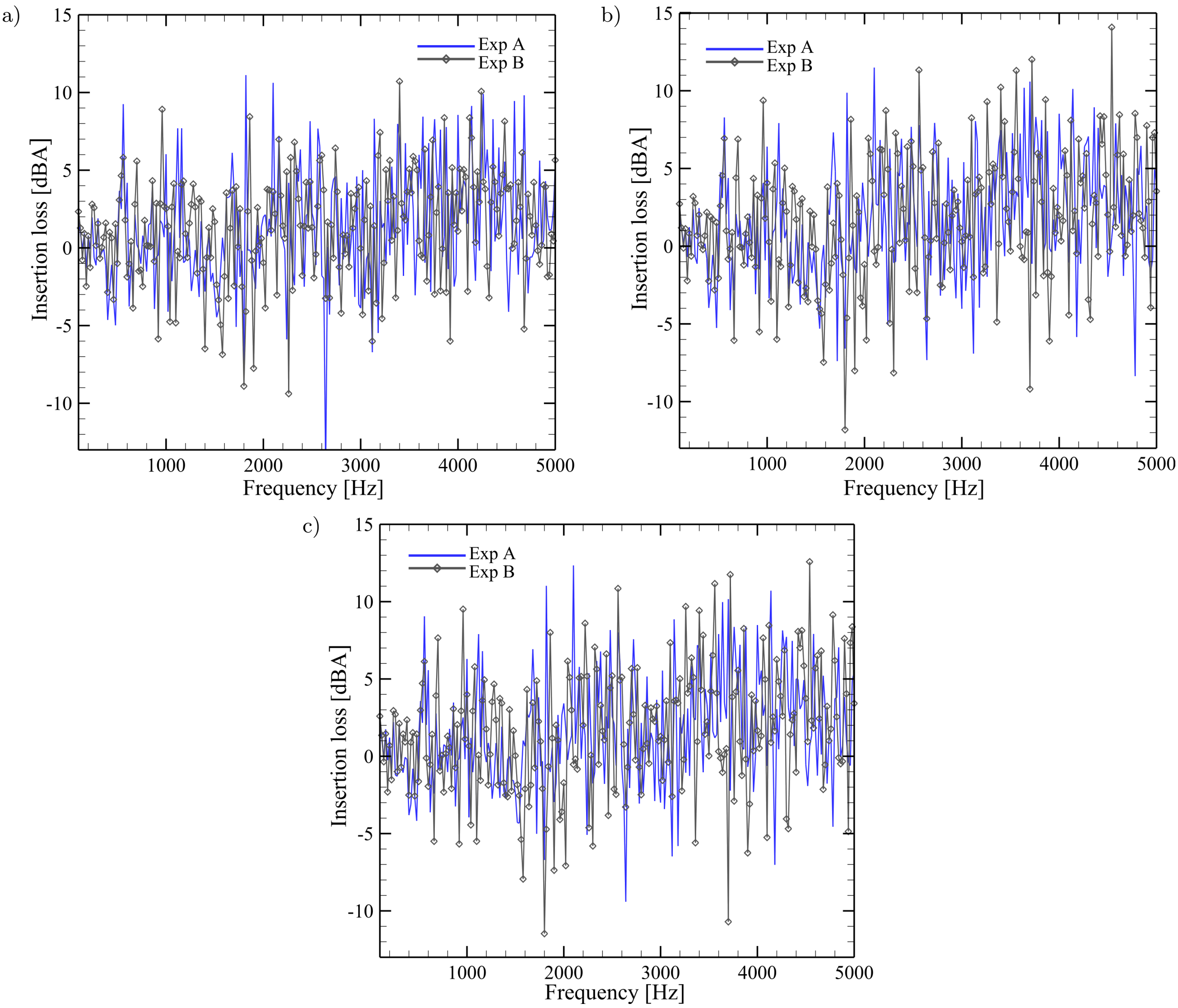

Fig. 4. IL_2 obtained by the plenum window with HRs (attached 90° jagged flap) when comparing with the case of without resonators for experiments A and B: a) white noise, b) traffic noise, c) construction noise.

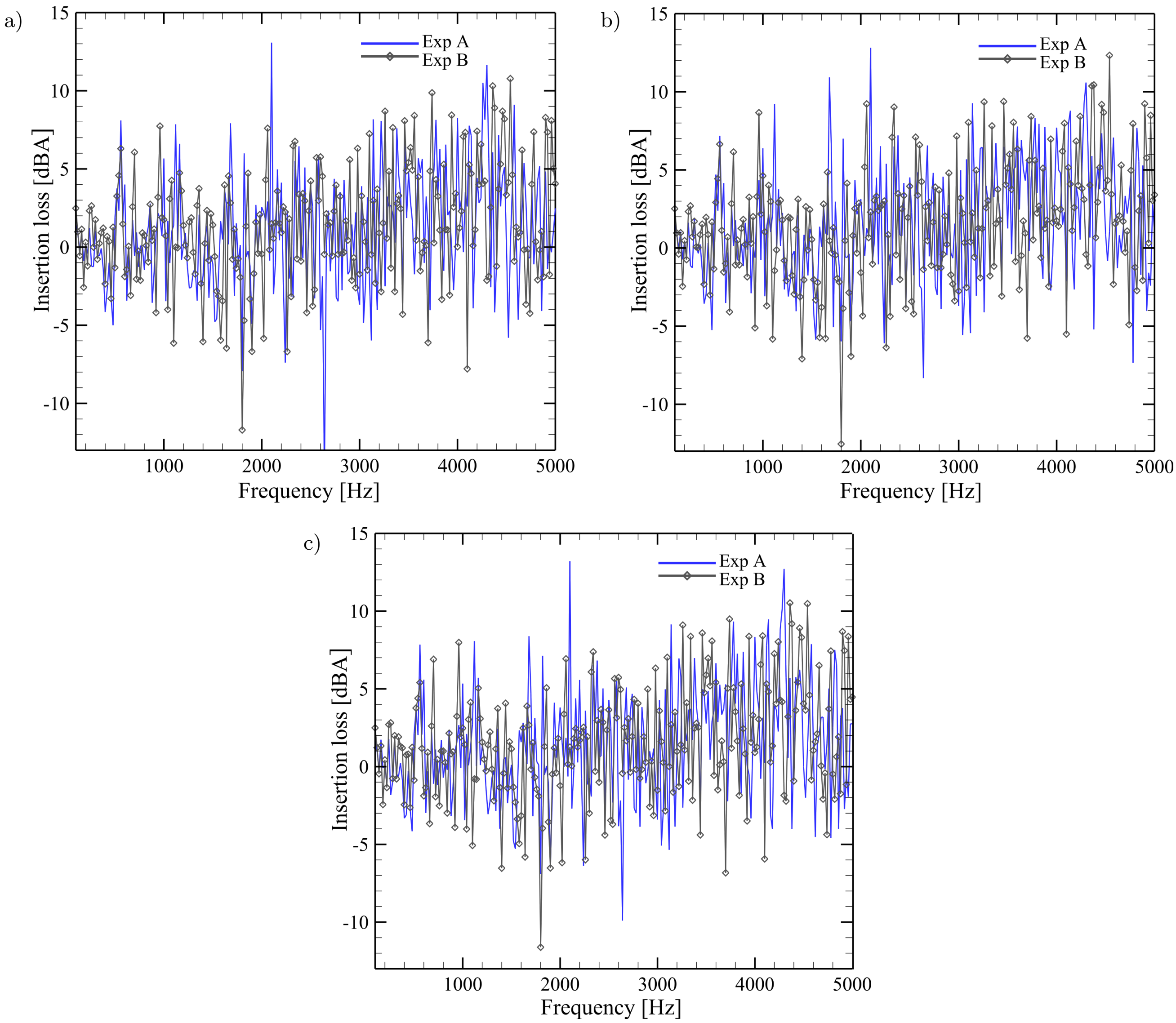

Fig. 5. IL_2 obtained by the plenum window with HRs (attached 45° jagged flap) when comparing with the case of without resonators for experiments A and B: a) white noise, b) traffic noise, c) construction noise.

4. Conclusions

A plenum window with incorporation of rectangular HRs was tested in a reverberation room. The effects of jagged flap on reducing strength of possible diffracted noise over the edge and gap of the plenum window was also investigated in the present studies. Two types of experiments were conducted by varying the positions of the noise source where white, traffic and construction noises were examined during each set of experiment. When the noise source was located at the central line of the plenum window, the plenum window with HRs was able to mitigate 8.5 dBA, 8.9 dBA and 8.2 dBA of white, traffic and construction noises, respectively, compared with the case of without window. These amounts of noises that mitigated by the plenum window were slightly higher than the case where noise source was diverged 30° away from the central line of the plenum window due to some of the noises might be directly propagated through the opening of the plenum window before they were reflected by the glass pane and the wall of reverberation room. The effects of jagged flaps on the acoustical performance of the plenum window were negligible due to non-optimised geometry of the jagged flap and little amount of diffracted noise. The HRs had the best performance in the frequency region between 900 Hz to 1300 Hz which was slightly higher than the estimated resonance frequency due the location of the glass pane which blocked the direct propagation of noise from source to the receiver. In this narrow frequency range, the plenum window with HRs was able to attenuate additional 1.7 dBA, 1.9 dBA and 1.6 dBA of white, traffic and construction noises, respectively, compared with the case of without resonators. Further studies are required to optimise the designs of the HRs and the jagged flap in order to attenuate higher noise level in wider frequency range.

Acknowledgments

This material is based on research/work supported by the Singapore Ministry of National Development and National Research Foundation under L2 NIC Award No. L2NICCFP1-2013-8 and the Key Program of National Natural Science Foundation of China (No. 11832009).

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