Title: A hybrid approach to active and passive noise control for open windows

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Abstract:

This research focuses on the use of an open window with an active noise control (ANC) system and a splitter silencer to improve the attenuation level of broadband noise. A similar idea has been previously attempted, with the splitter silencer and loudspeaker inside a duct. However, in this research paper, an open window assumes a short-length duct that it is not long enough to obtain a large noise reduction from the splitter silencer. Because, the noise reduction by splitter silencer depend length that the longer the better. Through our previous research, we achieved noise reduction at an open window with an array of ANC units, which collocated a reference microphone with a loudspeaker. But this system had a limitation in high-frequency noise reduction because of the distance of each loudspeaker from next loudspeaker. Thus, this research combines the collocated ANC system and the splitter silencer. We choose a 50% open ratio for the splitter silencer, and the silencer is equipped that four reference microphones located at the front side and in four loudspeakers located at the rear side to generate anti- noise for indoor. The unit has four loudspeakers and four reference microphones. The thickness, width, and length of the splitter silencer are 6 cm, 48 cm, and 12 cm, respectively. The experiment implemented two splitter silencer units for the 8-channel ANC system at an open window (24 × 48 × 12 cm). The experimental results showed that the part of the splitter silencer attenuated noise in the high-frequency region of above 2 kHz. Moreover, the ANC system improved the 2 to 10 dB attenuation level from 200 Hz to 2 kHz. Finally, total attenuation level reach 2 to 17 dB above 200Hz.

1. Introduction

Active noise control (ANC) is a technique that has been used to reduce noise [1], and it has been applied to air-conditioning ducts [2], ear protectors [3], and car engines [4]. These applications utilized ANC to achieve noise reduction together with passive noise control (PNC). For example, a duct attenuates high-frequency noise, whereas a loudspeaker attenuates low-frequency noise, which propagates the duct as a plane wave. On the contrary, there is a demand to control noise in large spaces using an open window. In this case, an ANC system must tackle all frequencies without the use of PNC. In particular, the problem of using an ANC system for the open-window application is the difficulty associated with reducing noise in high-frequency regions for large zones. Many researchers have tried multi-input and multi-output (MIMO) ANC systems to achieve noise reductions for open windows [5–7]. However, MIMO ANC systems have bottlenecks with the increasing amount of computation required by the controller, as well as with the increased cost incurred to achieve this requirement. In order to solve this problem, one of the research teams implemented an array of ANC units, which collocated between loudspeakers with a reference microphone using the open window

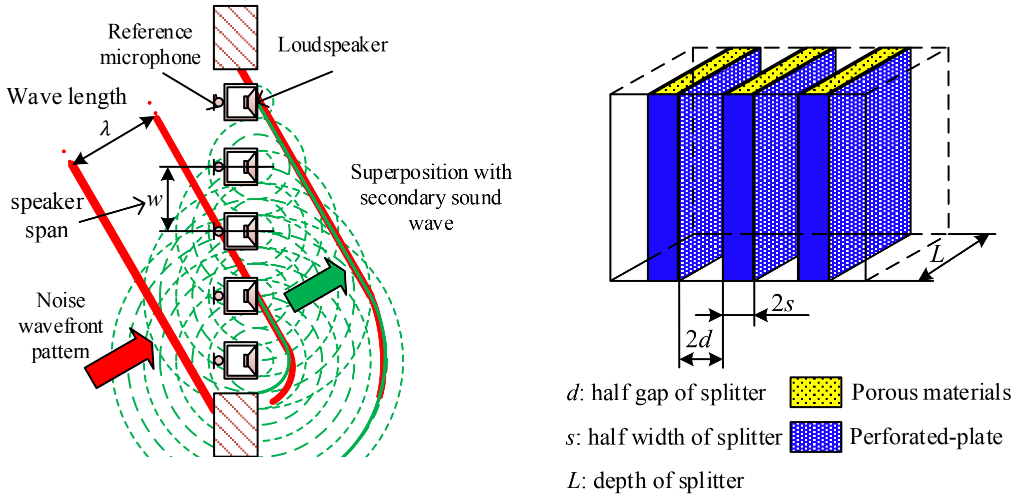
[8]. This approach, called a decentralized system, uses only reference signals and a loudspeaker for each ANC unit. According to the Huygens–Fresnel principle, the array of collocated units can make the same wavefront pattern of noise that passes through the array. Thus, the decentralized system be able to make large quiet zone behind the array. Moreover, this arrangement resulted in noise reduction for another noise incidence, plural noise sources and moving noise source. Therefore, an actual ANC system be able to work for any noise with a fixed adaptive filters that were adapted by a normal incidence of noise. In this scenario, the noise source is assumed to be a plane wave, and it is recommended that the distance of each secondary source is shorter than half of the wavelength of noise to obtain noise reduction [9].
The extent of noise reduction in high-frequency regions using an open window will depend on the density of the loudspeaker. However, the array of high-density units will fill in the open space of the window.

In this paper, we proposed a hybrid approach using both ANC and PNC for an open window. This approach applied a splitter silencer, which is a popular in air-conditioning ducts, ventilation, and other applications. Furthermore, the splitter silencer is combined with loudspeakers in the ANC system. A hybrid approach has been previously applied using a duct, as reported in a 1987 U.S. patent [10] for a hybrid active silencer; however, the open window has problems, such as the thickness of the window, which is short when it assumes the duct length to use a splitter silencer. In particular, the performance of splitter silencers depends on the length, width, and open ratio [11]. Meanwhile, ANC reduces noise with the condition of using the silencer splitter at the open window. Thus, in this study, we fabricated splitter silencers with loudspeakers to investigate the performance of the hybrid approach using both ANC and PNC.

Section 2 shows the basic concept of the open-window ANC with collocated units for this hybrid approach. Section 3 describes the fabrication of a splitter silencer with a loudspeaker and a chamber with an opening for experiments. The splitter silencer has four loudspeakers as one unit. The opening of the chamber is set as 2 splitter silencer units, and the chamber is made to measure the performance of these structures, which are the same ones used in the hybrid approach. Section 4 discusses a control method for the loudspeaker as an ANC system. Section 5 details our experimental results. Two units of the hybrid structure are set on the opening of the chamber, and the open ratio is 50%. Noise sources are band-limited white noise with 100 Hz to 2 kHz, white noise, and train noise. The adaptive filter of the ANC system was updated. After convergence, the adaptive filter was fixed and used for other noise sources (white noise and train noise). On the basis of the results, we determined that the hybrid approach using both PNC and ANC effectively reduces noise.

2. Basic concept of an ANC window

The MIMO ANC system is necessary to obtain a large attenuation area as an open window, especially at higher frequencies. With additional loudspeakers, this system can create a quite an area. Hence, in previous works, we chose an arrangement as the Figure 1(a) in which the array of ANC units is set on a grille at the open window, and each ANC unit equips a loudspeaker and a reference microphone.



(a) Active acoustic shielding[8] for open window (b) splitter silencer

Figure 1 Concept of ANC system for open window

According to the Huygens–Fresnel principle, the array can generate the same wavefront pattern as the noise that goes through the array. Moreover, collocated units allow another incidence wave with the same fixed filters after the filters have been updated [8]. For our previous work using an open window, we choose a distance of 0.125 m between each speaker. The results showed that noise was reduced below 1.6 kHz—a frequency close to the spatial Nyquist frequency of 1.38 kHz (c/2w), where *c* is the sound of speed and *w* is the distance between each speaker. Therefore, a high-density arrangement of the speakers is necessary to achieve noise reduction for high-frequency regions. At the same time, the number of MIMO systems must increase for noise reduction at high-frequency regions, and the open ratio of window must decrease; otherwise, the size of the speakers would become small. With small loudspeakers, it is difficult to generate low-frequency sounds. Hence, we chose a splitter silencer as Figure 1(b) for high-frequency attenuation.

3. Fabrication of the splitter silencer

This section describes the fabrication of a splitter silencer for the hybrid approach. The splitter silencer is a popular instrument for noise reduction in ventilation systems, and there has been research to determine and improve its operational mechanisms [11]. Saito et al. (1978) investigated noise-reduction in ducts and indicated how to decide on parameters for the splitter silencer [12]. Their research showed curves of sound attenuation performance of the splitter with a few parameters that are summarized by splitter size, open ratio, and materials. Helmut (1987) also described how to calculate the specific damping of the splitter [11]. Hence, these research studies indicated that the length of the splitter silencer to the axial direction is effective for noise reduction when keeping the open ratio of the duct. However, our target is an open window that is normally shorter than the duct. Although the open window is limited by the thickness as a duct length, we choose the splitter silencer dimensions such that the splitter silencer still works for high-frequency noise.

Figure 2 shows fabrication of a unit for the splitter silencer with an ANC system for open windows. Figure 3 shows the fabrication of a chamber and the arrangement of splitter silencer and primary source as Figure 3(a).

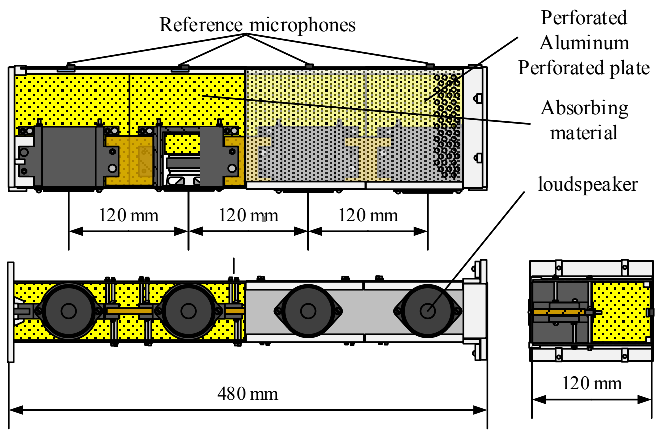
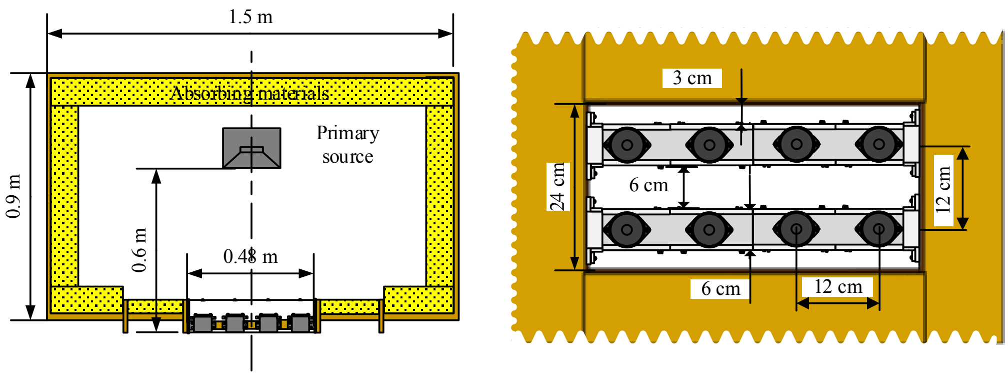


Figure 2 Multi view projection of a unit of splitter silencer with loud speaker



(a) Top view (b) Front view at opening of chamber

Figure 3 Arrangement of splitter silencer at chamber with opening.

First, we choose the distance between each loudspeaker to achieve the highest ANC noise reduction, as described in our previous paper [8]. In this paper, we choose a 12 cm distance between loudspeakers, and the spatial Nyquist frequency is 1433 Hz and the diameter of the loudspeaker is 5.25 cm (to keep the space open). Second, the splitter has a 6 cm thickness, 48 cm width, and 12 cm length so that the open part is 50%, as shown in Figure 3(b). In previous work [13], the prototype of the splitter silencer did not use front and rear plates. In this research, the silencer does use these plates. In particular, the splitter is thicker than the gap between splitters to achieve better attenuation. However, a window has a thickness limit, and we choose 12 cm as twice the gap distance between splitter silencers. Finally, the chambers are fabricated with wooden boards and absorbing materials. They have a 1.5 m length, 0.9 width, and 1.2 m height, and the opening is 0.48 m in length and 0.24 m in height for two ANC units as Figure 3(b).

Figure 4 shows the attenuation level at 1 m in front of the center of the opening part. A primary source is set at 0.6 m inside of the chamber from the center of the opening and generates white noise. The green bar compares measured sound pressure levels under the conditions of fully open and when two splitter silencers are set. The charts calculated from the references [11, 12] are shown in blue and red. For reference, the red symbols show the values considering 70% design margin. The result shows that the splitter silencers can obtain more than 6 dB attenuation above 1.6 kHz, and, in this paper, a silencer is used to overcome the above limitation of the ANC system.

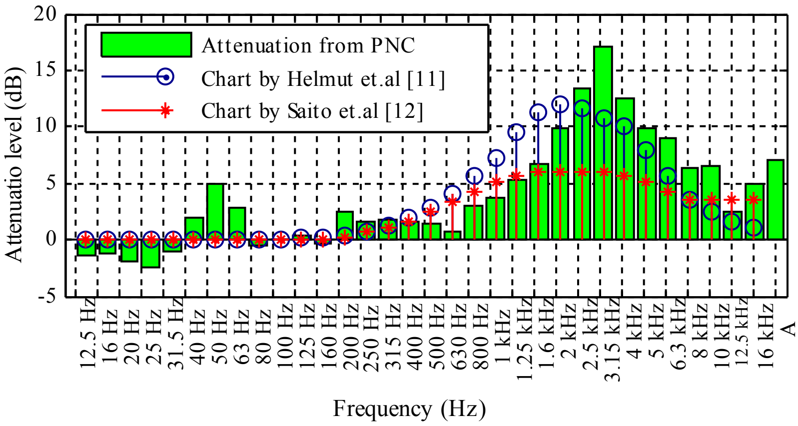
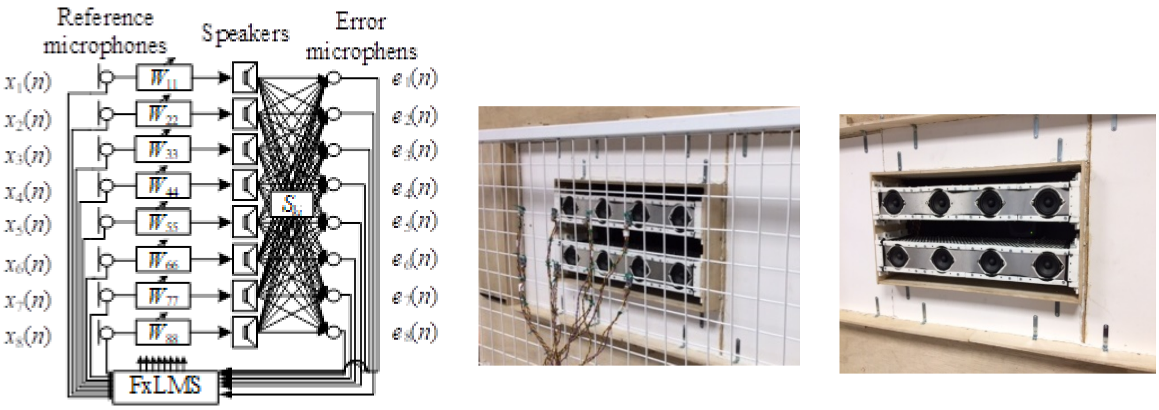


Figure 4 Attenuation level at 1m in front of open window.

4. ANC algorithm

This section shows the algorithm of ANC used to control the eight loudspeakers of the splitter silencer. The algorithm applies a method based on multi-channel FxLMS, with ANC units that is collocated a reference microphone and a loudspeaker from previous research using open windows [8]. The method uses multi-channel FxLMS without cross-adaptive filters, as shown in Figure 5(a), by the following procedures. First, the primary source chooses the band-limited white noise around the spatial Nyquist frequency—in this case, we choose 100Hz to 2 kHz. Second, after updating the adaptive filters, these filters were fixed and the system was controlled by the fixed filters. Hence, error microphones can be removed, and the system assumes a feedforward control.

According to the Huygens–Fresnel principle, the units generated can make the same wavefront pattern for the frequency of band-limited white noise. In consequence, the fixed filter can be used for to reduce other noises in this frequency region. Figure 5(a) shows an 8(1-1)-8 FxLMS, which has eight reference microphones, eight loudspeakers, and eight error microphones.



(a) block diagram ANC system (b) 8 error microphones (c) Without microphones

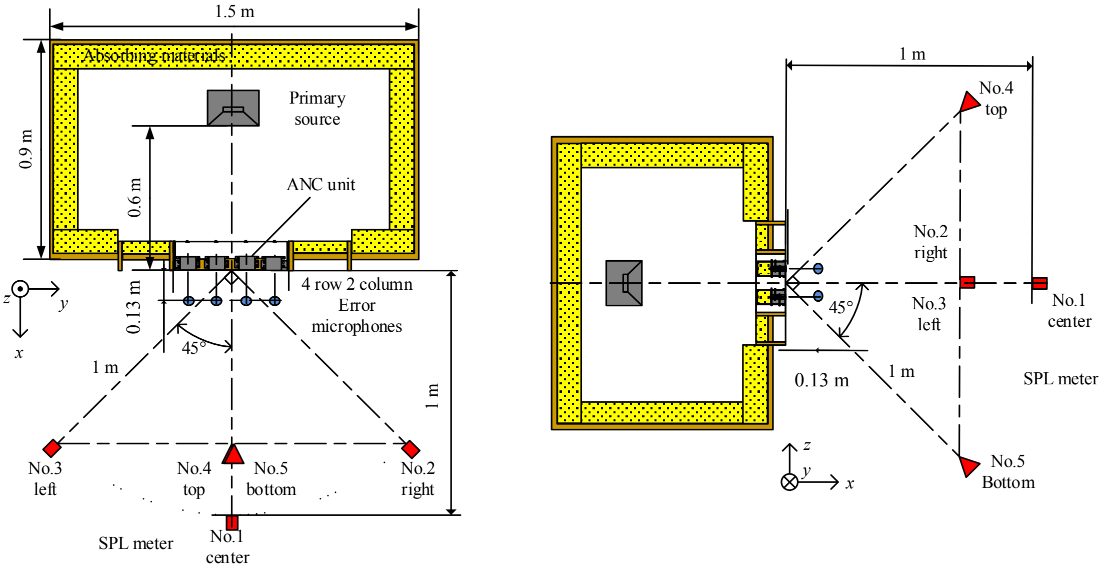
Figure 5 Block diagram and the view of the ANC system with 8 error microphone and without microphones

Equation 1 shows the update of the adaptive filters. Figure 5(b) shows the condition of updating part. Figure 5(c) shows the after update filter and removing error microphones.

$$\mathbf{w}_{ii}(n+1) = \mathbf{w}_{ii}(n) - \mu \sum_{k=1}^{8} \{ \hat{\mathbf{s}}_{ki}(n) * \mathbf{x}_{i}(n) \cdot e_k(n) \} \quad (i = 1,2,\cdots 8) \qquad (1).$$

5. Experimental results

This section shows the experimental results with the hybrid approach of an ANC window. Figure 6 shows the arrangement of experiments, with the primary source set at 0.6 m inside the chamber from open space. These error microphones also measured error signals to determine the performance of ANC parts as a relative sound-pressure level. Furthermore, there are five monitors to check global noise reduction at 1 m in front of the open space, with the positions places in five different directions, which are front, left, right, top, and bottom, with a 45-degree angle. The primary source uses three types of sounds: band-limited white noise from 100 Hz to 2 kHz, white noise, and train noise. There are three conditions for the measurements: opening fully, setting the splitter silencers, and turning on the ANC system. For this research, every condition used the fixed filters updated by the band-limited white noise.



(a) Top view (b) side view

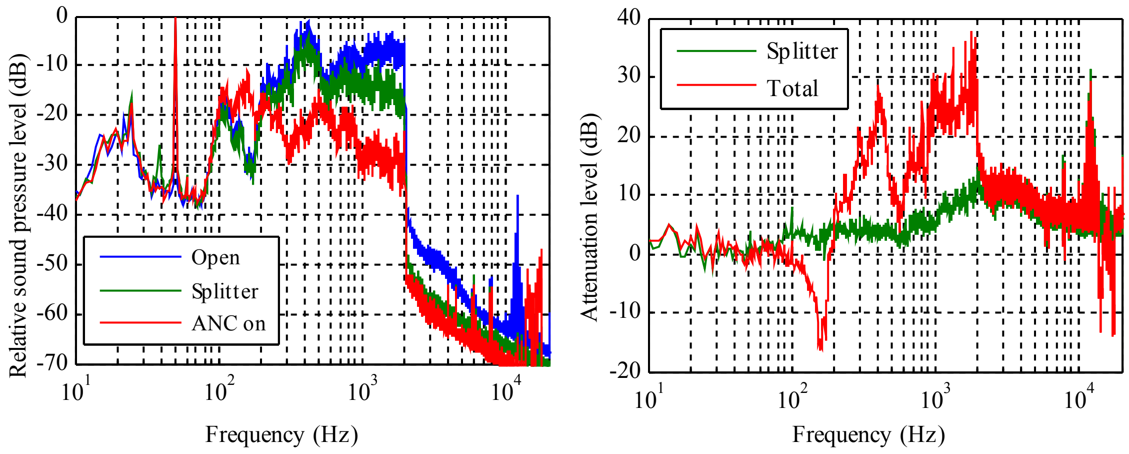
Figure 6 Arrangements of experiments with, green circle shows 8 microphones in front of 0.13 m from open window, the red triangle and rectangles shows the positon of sound pressure level meter for measurements with 1m distance from the center of the opening. Figure 6(a) shows the top view and Figure 6(b) shows side view.

5.1 Error microphone signals

Figures 7, 8, and 10 show the average relative sound-pressure levels and attenuation levels among the error signals under three conditions. First, the blue line shows that the open space has no structure—it just goes through noise. Second, the green line shows that the splitter silencers are put on open spaces for only PNC performance. Finally, the red line shows the ANC system turning on and the total attenuation from PNC and ANC.

(i) Band-limited white noise

Figure 7 focuses on the maximum performance of the ANC part because the fixed adaptive filter by this condition use for every other condition. Thus, the residue between the red and green lines shows the maximum attenuation level of the fixed filter for an ANC system. Moreover, the noise source use band limited white noise form 100 Hz to 2 kHz, and ANC part only target these frequency regions. Figure 7(b) show the splitter silencer has 10 dB attenuation level above 2 kHz because the noise source does not include high frequency by this setting. Thus, the sound pressure level from noise source has already been close to background noise in this case that noise source dose not generate high frequency noise. The system obtains 10 to 20 dB attenuation around 200 to 2 kHz by the ANC system. At around 140 Hz and 500 Hz there is increased or no attenuation because of the resonance of the chamber.



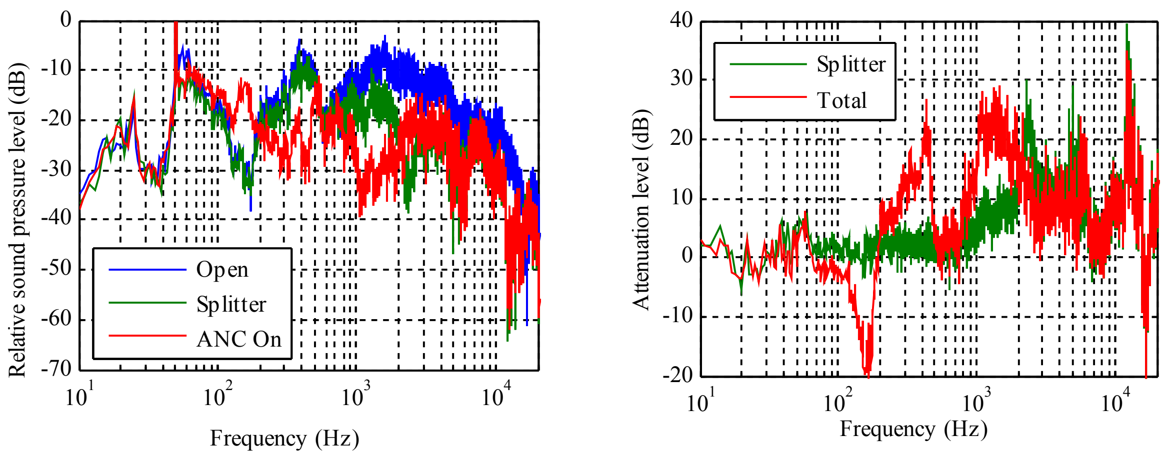
(a) Average of relative sound pressure level

(b) Average of attenuation level

Figure 7 Average of power spectrum among error signals as Figure 7(a) and attenuation level as Figure 7(b) under full open window (blue line), set splitter silencer (green line) and using ANC system (red line) with band limited white noise 100 Hz to 2 kHz as the primary source.

(ii) White noise

Figure 8 shows average relative sound-pressure levels and attenuation levels under white noise. The condition also uses the fixed filter updated by the band-limited white noise (same as in Figure 7). Each line shows the same means as those in Figure 7. The graph shows an improvement in the total attenuation level around 200 to 500 Hz and 1 k to 2 kHz with the ANC system while keeping the attenuation of PNC above 2 kHz. At around 100 to 200 Hz, there is increased noise.



(a) Average of relative sound pressure level

(b) Average of attenuation level

Figure 8 Average of power spectrum among error signals as Figure 8(a) and attenuation level as Figure 8(b) under full open window (blue line), set splitter silencer (green line) and using ANC system (red line) with white noise as the primary source.

(iii) Train noise

Figure 9 shows the amplitude of error microphone no. 2 with train noise. The *x*-axis is the time domain and the *y*-axis is the amplitude. The blue line shows the open window, the green line shows the setting of the splitter silencer, and the red line also shows using ANC. The ANC system also uses the fixed filters that were updated by the band-limited white noise from 100 to 2 kHz. Hence, the system can obtain noise reduction from the first wave. Figure 10 shows the average power spectrum and attenuation levels among error signals.

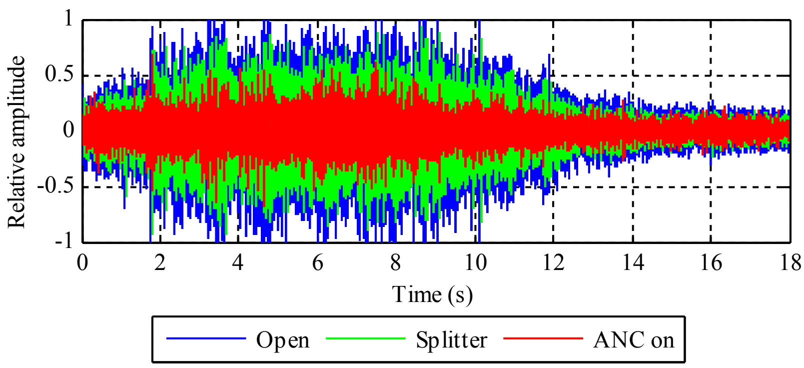
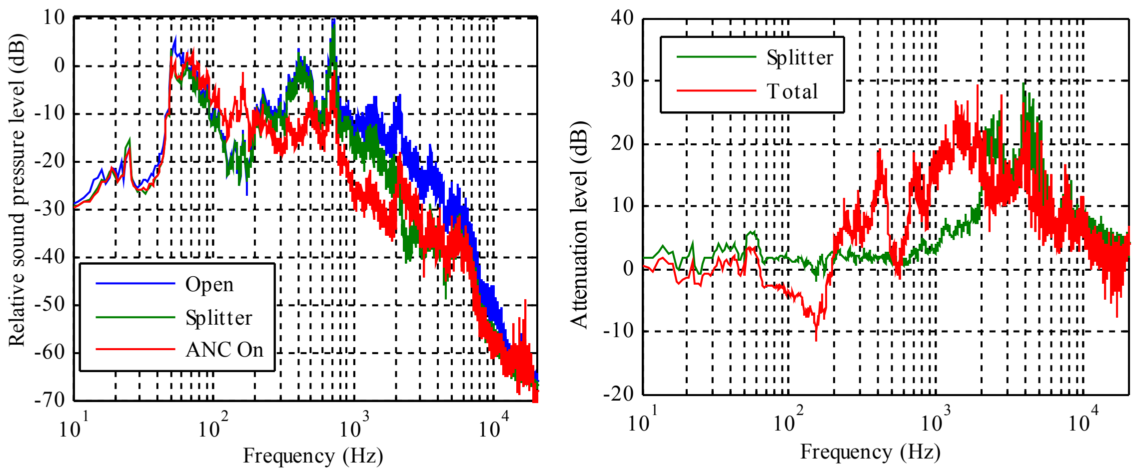


Figure 9 Amplitude by time domain at No.2 error microphone under open window (blue line), set splitter silencer (green line) and using ANC system (red line with train noise from primary source

Figure 10 also shows averaged each by each 1 sec duration from 0 to 18 sec. The results show the fixed filter obtained noise reduction from 200 to 500 Hz and 600 to 2 kHz.



(a) Average of relative sound pressure level

(b) Average of attenuation level

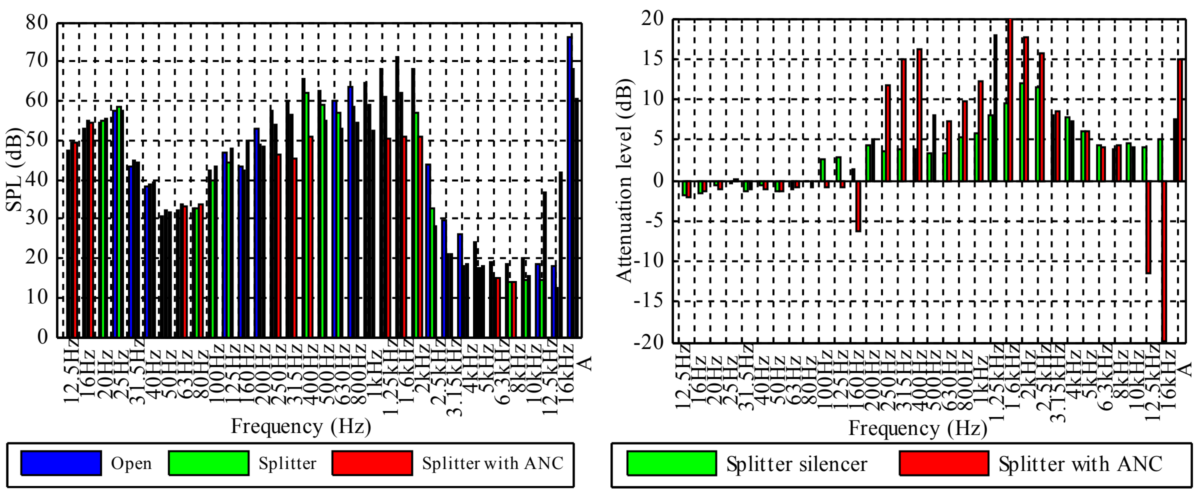
Figure 10 Average of power spectrum among error signals as Figure 10(a) and attenuation level as Figure 10(b) under full open window (blue line), set splitter silencer (green line) and using ANC system (red line) with train noise as the primary source.

5.2 Sound-pressure levels at monitor points

Figures 11, 12, and 13 shows the average sound-pressure levels with equivalent continuous sound-pressure levels (Leq, 20 sec) and attenuation levels among five monitoring points located at a 1 m distance from the center of the window. The primary source also used band-limited white noise from 100 to 2 kHz, white noise, and train noise. There are three conditions. First, the blue line shows a condition that is the open window; thus, noise goes through the window. Second, the green line shows a condition in which the splitter silencer is set; hence, the splitter silencer works for the high-frequency region as PNC. Third, the red line shows a condition in which the splitter silencer has ANC on; therefore this line shows the total attenuation level achieved using the hybrid approach. Every condition uses the fixed filter that was updated by band-limited white noise from 100 to 2 kHz.

(i) Band- limited white noise

Figure 11 shows the result when the primary source is band-limited white noise with 100 Hz to 2 kHz. The graph indicates that the ANC system improves the attenuation around 200 to 2 kHz with the splitter silencer behind error microphone array. However, at 500 to 800 Hz there is only a 3 dB improvement because the primary sound level is small at this frequency range as discussed in the last part of this section.



(a) Average of sound pressure level (b) Average of attenuation level

Figure 11 Average of sound pressure level as among 5 monitor point at 1 m distance from the center of the window under the conditions that primary source is band limited white noise 100 Hz to 2 kHz as figure 11(a). Figure 11(b) shows average of attenuation levels. The blue line shows that the window is open, the green line shows setting the splitter silencer at the opening and the red line shows using active noise control.

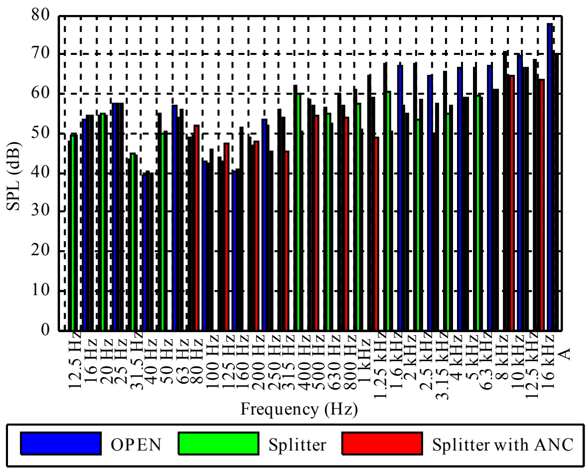
Table 1 shows the overall attenuation level at each monitor point, with the PNC of the splitter silencers and the total attenuation levels form the splitter silencers and ANC. The attenuation level in front of each window is 19 dB.

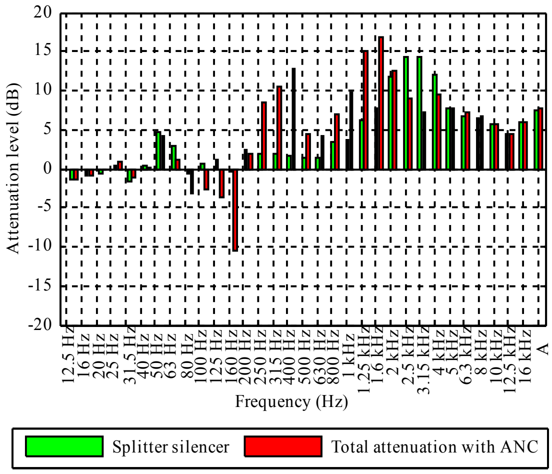
Table 1 Overall attenuation level from passive noise control of splitter silencers and total attenuation from passive and active noise control of the approach at five monitor point under using bandlimited white noise

	No.1 (center)	No.2 (right)	No.3 (left)	No.4 (top)	No.5 (bottom)
PNC [dB]	8.1	7.9	8.3	6.4	6.9
PNC & ANC[dB]	19	13	13	14	12

(ii) White noise

Figure 12 shows the result when the primary source is white noise. The graph indicates that the ANC system added the attenuation around 200 to 2 kHz. At around 500 to 800 Hz, there is not much attenuation from ANC because of the resonance of the chambers at the error microphones. The overall attenuation level is around 7 dB because the dominant frequency is the high-frequency region of white noise.





(a) Average of sound pressure level

(b) Average of attenuation level

Figure 12 Average of sound pressure level among 5 monitor point at 1 m distance from the center of the window under the conditions that primary source is white noise as figure 12(a). Figure 12(b) shows average of attenuation levels. The blue line shows that the window is open, the green line shows setting the splitter silencer at the opening and the red line shows using active noise control.

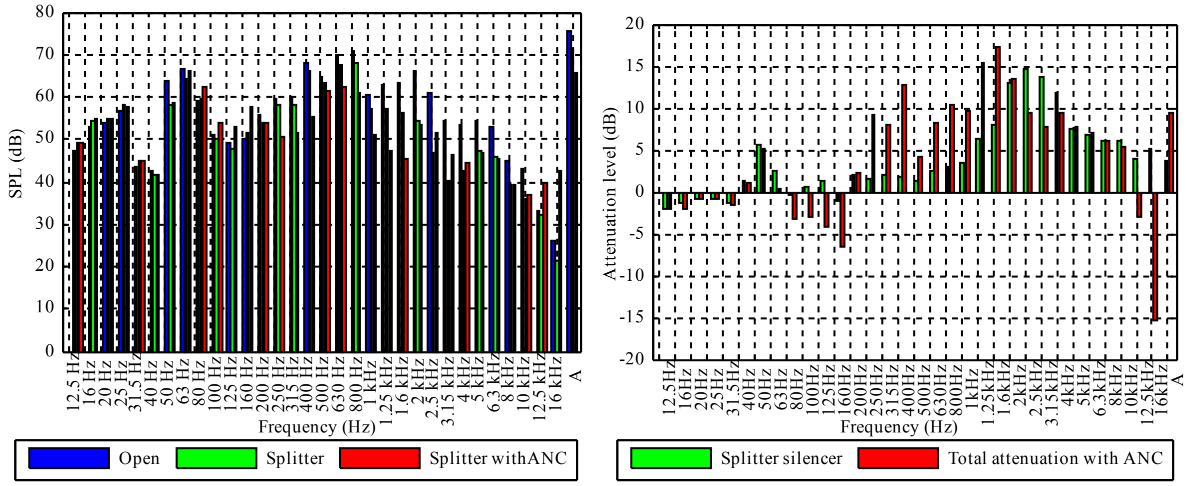
Table 2 also shows the overall attenuation level at each monitor point, with the PNC of the splitter silencer and the total attenuation level from the splitter silencer and ANC. The over all attenuation level in front of the window reaches 8 dB.

Table 2 Overall attenuation level from passive noise control of splitter silencers and total attenuation from passive and active noise control of the approach at five monitor point under using white noise

	No.1 (center)	No.2 (right)	No.3 (left)	No.4 (top)	No.5 (bottom)
PNC [dB]	7.1	8.4	9.3	5.7	5.7
PNC & ANC[dB]	8.3	8.3	9.3	5.6	6.3

(ii) Train noise

Figure 13 shows the result when the primary source is train noise. The graph indicates the hybrid system can work for broadband frequency. Moreover, the overall attenuation reaches 9 dB because the dominant frequency of the train noise is around 400 to 800 Hz.



(a) Average of sound pressure level (b) Average of attenuation level

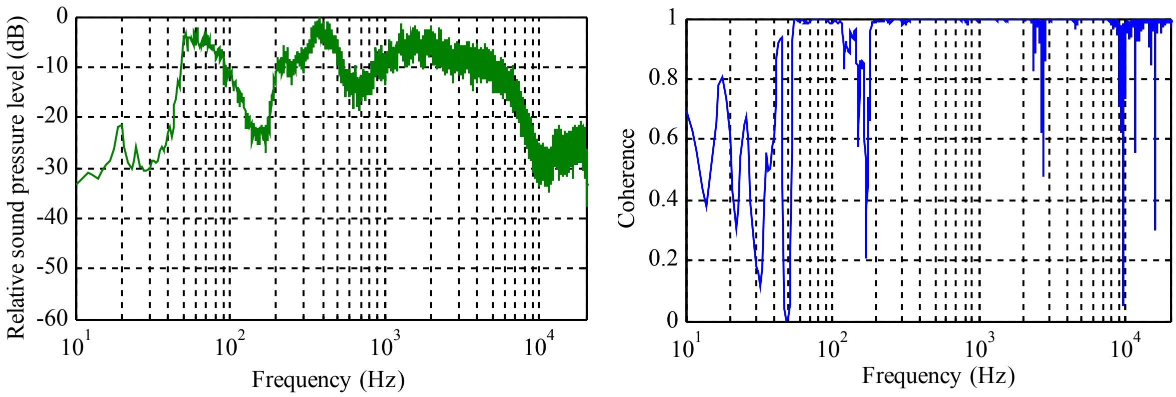
Figure 13 Average of sound pressure level among 5 monitor point at 1 m distance from the center of the window under the conditions that primary source is train noise as figure 11(a). Figure 11(b) shows average of attenuation levels. The blue line shows that the window is open, the green line shows setting the splitter silencer at the opening and the red line shows using active noise control.

Table 3 also shows the overall attenuation level at each monitor point, with the PNC of the splitter silencer and the total attenuation level from the splitter silencer and ANC. The attenuation level in front of the window reaches 12 dB.

Table3 Overall attenuation level from passive noise control of splitter silencers and total attenuation from passive and active noise control of the approach at five monitor point under using train noise

	No.1 (center)	No.2 (right)	No.3 (left)	No.4 (top)	No.5 (bottom)
PNC [dB]	4.1	3.2	3.2	4.2	3.6
PNC & ANC[dB]	12	8.1	9.8	7.6	7.2

Figure 14 shows the average relative sound-pressure level at eight reference microphones under conditions of setting the splitter silencer when the primary source is white noise (left). The graph on the right shows the coherence between reference microphone no. 6 with error microphone no. 6. These graphs reveal that the primary-speaker position is difficult to generate 183 Hz by the chamber of mode (0, 1, 1). The drop around 500 to 800 Hz is also the third mode of the chamber. This is considered to be the reason why the attenuation performance of ANC is degraded at these frequency regions.



(a) averaged power spectrum 8 refenrece signals (b) cohernece

Figure 14 Averaged power spectrum 8 error microphone when primary source is wthite noise (a), and a cohernece between the error signals no. 6 and the refence signals no. 6 (b)

Conclusions

In this paper, we proposed a hybrid approach using both ANC and PNC to improve the attenuation level of an ANC window. The system applies a splitter silencer with loudspeakers at end of the splitter for an open window. The difference between this research and that using traditional ANC splitter slicers is that the length of the splitter silencer for the window is too short to assume a duct. Therefore, we make splitter silencers that are 6 cm in width and 48 cm in length to cover 50% of the open window (24 × 48 cm). The splitter length is 12 cm. The size is chosen from the design charts of Helmut [11] and Saito et al. [12], and thus the performance reaches 5 dB to 17 dB above 1.6 kHz.

The total attenuation with the ANC system was 2 to 17 dB above 200Hz at the error microphones, and the five monitor points were 1 m from the open window. Therefore, the attenuation of 200 to 1.6 kHz was derived from loudspeakers as the ANC system, and the attenuation over 2 kHz was derived from the splitter silencer as PNC. Moreover, the system works with a fixed filter updated by band-limited white noise (100 to 2 kHz) and train noise. In both cases, the system achieves noise reduction with ANC in the region 200 to 2 kHz. Future work should investigate the effect of the other incidence wave. In previous work, a collocated ANC system with a fixed filter worked for another incidence [8]; however, the system was physically limited by the distance of each loudspeaker [9]. Moreover, the distance from a reference microphone to a loud speaker of this splitter silencer is longer than previous ANC units [8]. Thus, it is not ideal case and it will cause a degradation of attenuation level for another incidence wave.

Acknowledgements

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