Investigation of a smart noise barrier for dual active and passive control of construction noise

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ABSTRACT

Construction noise generated from various powered mechanical equipment is mainly dominated by low-frequency sound components. A common practice to this severe noise problem for environmental protection is to block the acoustic transmission path between noise sources and sensitive receivers, in which noise barriers or acoustic enclosures are used to surround construction sites or powered mechanical equipment, respectively. Conventional passive noise barriers are generally made of aluminum, concrete, acrylic sheets or recycled materials, but it is not performed well for low-frequency noise. This research work is concerned with the investigation of a smart noise barrier for both active and passive control of construction noise. This hybrid-based noise barrier is made of two layers, one thick layer is a recycled composite material (i.e., a mixture of wood pellets and rubber particles) and the other one is a polyvinylidene fluoride (PVDF) thin-film. In view of the coupling design, the interaction of wood-rubber materials as a resilient layer can achieve good transmission loss at middle and high frequencies for passive noise control. In addition, recycling wood and rubber products into noise barriers is a sustainable technology that not only preserves the use of natural resources and also advances the engineering performance. In terms of active control, motivated by the high-quality piezo-actuator audio technology, PVDF thin-film materials are performed as a noise-cancellation speaker that can mitigate the low-frequency components of incident waves. To demonstrate the effectiveness of this dual-function noise barrier, a scale-down model is designed and tested in the in-house laboratory. Simple fabrication procedures of this barrier are also presented. It is expected that this study will bring a new idea for designing retractable and movable noise barriers/enclosures in open fields that can reduce the impact of construction noise for better environmental conservation.

1. Introduction

In Hong Kong, the construction industry that is a major economic pillar is expanding at a rapid pace. In this context, construction noise is a major problem due to the frequent use of construction machines for various construction activities, e.g., piling, drilling and excavation. A long-term exposure to high noise levels can cause an adverse and negative effect on psychological health, quality of life and working efficiency [1]. To alleviate this critical issue, vertical barriers are commonly used to separate noise sensitive receivers from noise sources. Through a direct measurement of the sound propagation paths (i.e., diffraction and transmission paths), the shielding effects of sound barriers can be well identified [2].

In real-world engineering conditions, the performance of passive-type sound barriers is strongly dependent on several factors, including material types, design dimensions, surface conditions, and geometric configurations [3-6]. In general, conventional barrier types are made of masonry, steel, concrete and wood materials [7]. Taking concrete as an example, it is hard to fulfill the requirements of simple construction and acceptable aesthetics [8]. To design environmental-friendly noise barriers, it is preferred to use low-cost, recyclable and lightweight materials. Wood and rubber composite materials have shown great potentials as a candidate for advanced barrier design, as it can increase tensile modulus and mechanical strength. In the literature, the sound insulation properties of wood-rubber composite panels were investigated by a four-microphone method [9]. The damping factor and acoustical coefficient of plywood/waste tire rubber composite panels were tested [10]. Waste tire rubber particles were also added to aggregate concrete to form a lightweight and sound insulation structure [11]. In addition, vertical barriers with porous surface materials and sound-dampening materials can be highly absorptive to reduce the reflective effect [12], such a design is suitable for roadside noise mitigation [13]. However, only using passive sound barriers (e.g., aluminum, metal, timber, acrylic, or vegetation) is not well effective to cover a wide range of frequency bandwidth, especially for low-frequency components [14]. The major reason is the acoustic wavelength of low-frequency noise is significantly longer than the thickness dimension of barrier structures to cause an inefficient coupling effect. Facing this challenging task, acoustic metamaterial structures have been proposed as a viable solution for low-frequency sound attenuation [15, 16].

As an alternative, covering a wider frequency bandwidth, we may integrate passive and active control together. By generating an anti-phase acoustic wave, unwanted sound can be cancelled based on the principle of superposition, which is called an active noise control technique. In laboratory tests, using a setup with microphones and speakers for data acquisition and noise attenuation was implemented for active control [17, 18]. Due to the limitation of active control, a coupling of active and passive control technologies is a simple but effective approach [19-21], which can broaden the frequency bandwidth for noise control with a higher efficiency. To attenuate noise levels in open fields, integrating sound masking techniques was evaluated [22] through embedding active noise mitigation elements in passive control barriers. Comparing with conventional loudspeakers with bulky coils and diaphragms, polyvinylidene fluoride (PVDF) is a new, smart and thin-film material with strong piezoelectric [23] and ferroelectric [24] properties. PVDF thin-film materials are not affected by electromagnetic interference and iron filling. In addition, they can be driven by an integrated circuit directly with a high-energy exchanging efficiency [25]. A transparent and flexible device, like a sandwiched membrane structure driven by PVDF, was fabricated and investigated [26, 27] to determine its acoustic characteristics and surface vibration modes. To improve the radiation of low-frequency signals using piezoelectric speakers, a tuck-shape structure was also proposed [28]. Utilizing PVDF devices in active noise control, a foam-PVDF smart skin for aircraft interior control was presented [29]. Furthermore, the performance of transparent thin-film speakers attaching on the surface of window as a secondary source for noise control was also tested experimentally [30, 31].

In this work, a dual-function noise barrier, coupling recycled wood-rubber composite panels and a PVDF thin-film speaker, is proposed for passive and active noise control. To reveal the effectiveness of this dual-function noise barrier, experimental studies are carried out in the in-house semi-anechoic chamber by a scale-down model. Noise reduction levels can be determined through the insertion loss measurement. Presented herein also shows the easy fabrication procedures of this dual-function noise barrier for future practical applications.

2. Fabrication methods and experimental setup

2.1 Fabrication of recycled composite material panels

According to the ASTM standard [8], acoustic tests of wood-rubber composite materials were conducted in the in-house semi-anechoic chamber. To prepare test samples, wood particles and rubber crumbs were bonded by epoxy resin. Three important factors, which may affect the sound insulation properties [9, 10, 12], include the size of wood particles, wood-to-rubber ratio, and thickness of the samples. Fine and coarse wood particles (1–2 mm and 3–6 mm in diameter) and rubber crumbs (1–3 mm in diameter) were used to prepare various test specimens in a cylindrical shape with different thickness values, i.e. 10, 15, 20 and 25 mm. Among all specimens, the diameter was set as 98 mm to fit the internal size of the standard impedance tube (i.e., 100 mm in diameter, B&K Type 4206), as shown in Figures 1(a) and 1(b). Pure-wood and pure-rubber specimens were also prepared for control experiments. A total number of 52 test specimens were fabricated as shown in Figure 1(c).

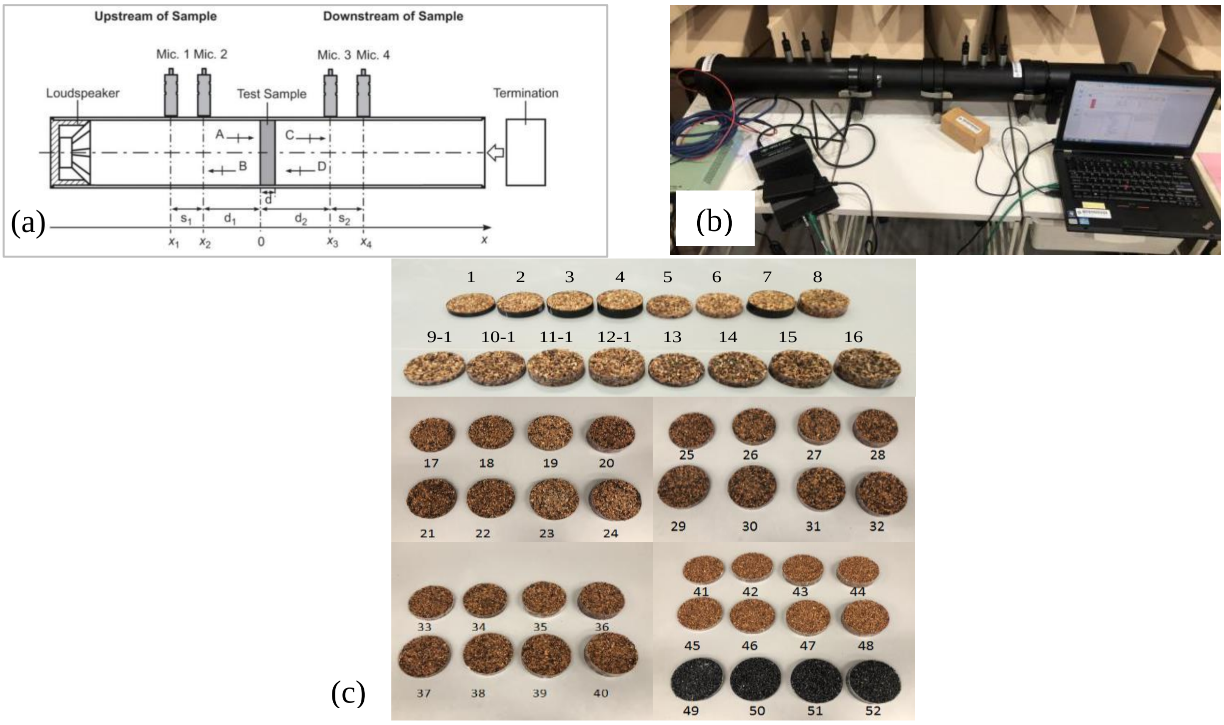

Figure 1. (a) Principle of using an impedance tube for transmission loss measurement; (b) a transmission loss tube (B&K Type 4206); and (c) 52 recycled composite material specimens.

2.2 Fabrication and characterization of a PVDF speaker

The design of a PVDF thin-film speaker covers three main parts: a vibrating PVDF diaphragm, surface electrodes made by silver ink, and a supporting structure made of acrylic materials. The supporting frame is used to secure the PVDF thin-film and control its vibration modes under the supply of electrical signals. In this study, a 280-µm thickness PVDF material was used as a thin-film speaker, see Figure 2. A silver ink paint was then used as electrodes on both surfaces of the PVDF thin-film. As PVDF is anisotropic in nature, it is important to orient the film in a proper way. Electrodes were then deployed along with the length direction to achieve a maximum displacement under the effect of voltage supply. When a voltage is applied to the film electrodes, it can create a mechanical strain in the film along the normal and in-plane directions. As the film is very thin, the strain along the normal direction can be ignored.

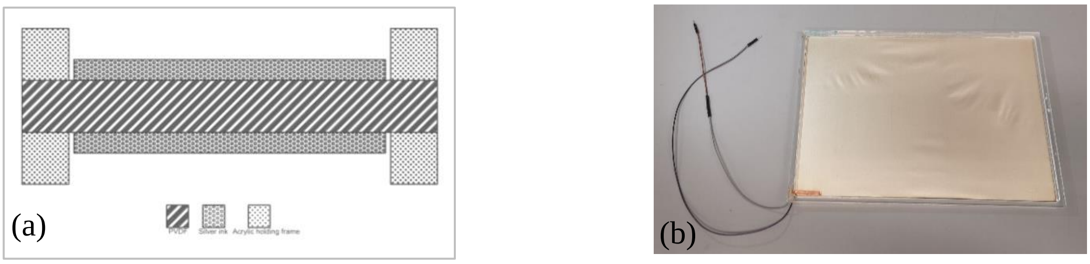

Figure 2. (a) Schematic diagram of a single PVDF thin-film speaker and (b) a PVDF thin-film speaker.

2.3 Fabrication of a dual-function noise barrier

To test the effectiveness of a hybrid barrier, a scale-down model was constructed in the in-house semi-anechoic chamber. The hybrid barrier consisted of nine rectangular wood-rubber panels and one PVDF thin-film speaker for dual passive and active control, see Figure 3. The scale ratio was selected at 1:4 as a miniaturized model for laboratory test. Each rectangular wood-rubber panel of 200 mm (length) × 140 mm (width) × 25 mm (thickness) was prepared, as shown in Figure 3(a). A 3-by-3 array frame structure (464 mm in height) was used to combine the wood-rubber panels and PVDF thin-film speaker together. Prefabricated and demountable components were utilized to simplify the assembly procedures. In practical applications, this setup is similar to modular structures for easy manufacturing and installation. There are three main steps to form a dual-function barrier, including: (i) prefabricated composite panels and a PVDF thin-film speaker independently; (ii) inserted the recycled composite panels and the PVDF thin-film speaker into a U-like framing structure; (iii) fixed the integrated modulus into the 3-by-3 array holding frame, as shown in Figure 3(b).

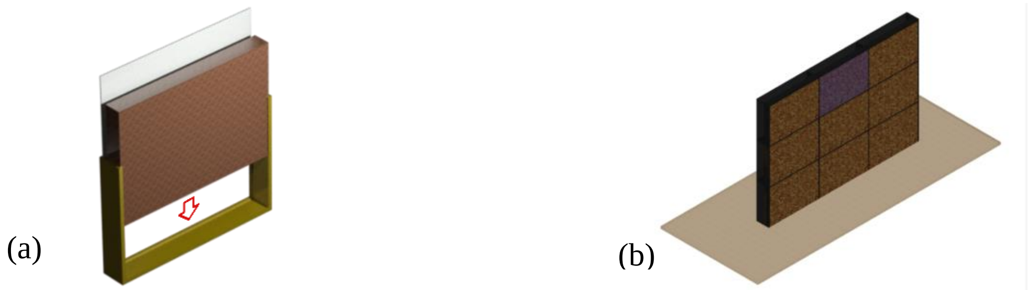

Figure 3. (a) A U-like structure with inserted PVDF thin-film speaker and recycled composite panel; and (b) a 3-by-3 array dual-function noise barrier.

We assume that the noise barrier can be extended infinitely. A two-dimensional profile between the separation distance and the height axis is investigated to reveal the distribution of sound effects, i.e., the sound pressure level (SPL), along the central line of the noise barrier. Research to determine the sound insulation properties was conducted by testing three cases, namely: (i) without any barrier; (ii) with only the passive barrier (wood-rubber composite panels); and (iii) with the dual passive and active control barrier (in the presence of a PVDF speaker). Measurements were recorded in the wave propagation direction along the central axis from the loudspeaker. The separation distance between the barrier and the microphone array was set at 50, 70, 90, 110 and 130 cm, respectively. The height of the microphone array was 30, 40, 50 and 60 cm, respectively. The measurement space was the separation distance and the microphone height along the centre line of the dual-function noise barrier. Schematic diagrams of the dual-function barrier and microphone array setup are presented in Figures 4(a) and (b). Phases of the secondary source can be manually tuned to minimize the effect of SPL at the measurement point (e.g., the separation distance of 50 cm and the microphone height of 30 cm), where is the centre point with a better shielding effect. [2] Pictures of the scale-down model setup (3-by-3 array frame structure) are shown in Figures 4(c) and (d). To simulate the situation of an infinite barrier, absorptive boundaries (triangle sound absorptive wedges in Figure 4(c)) were placed on both sides of the barrier to minimize the reflection and leakage of sound fields.

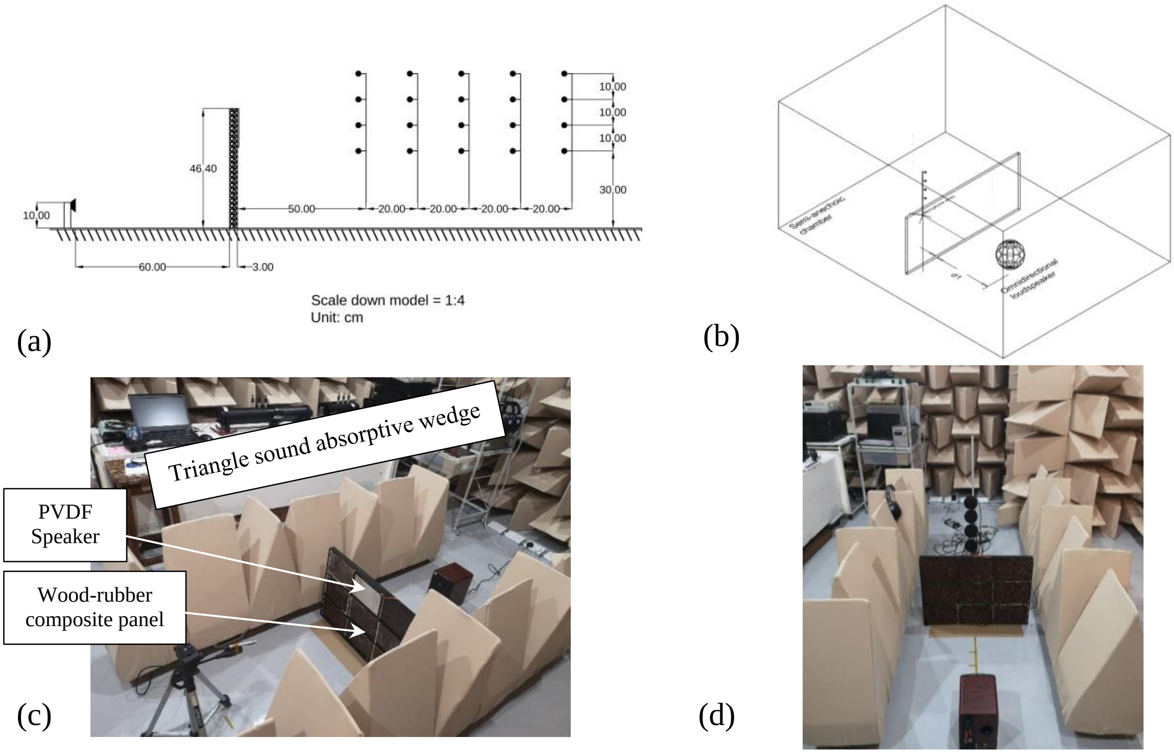

Figure 4. (a) and (b) Experimental setup of the scale-down model in the semi-anechoic chamber; (c) the dual-function barrier (3x3 array frame structure) with one microphone; and (d) the dual-function noise barrier (3x3 array frame structure) measured by a four-microphone array.

3. Results and discussion

3.1 Acoustic test of recycled composite materials

In Figure 5, we presented the acoustic results by comparing different ratios of wood-rubber particles, thickness of samples and size of wood particles. In Figure 5(a), the weighting ratio of wood and rubber particles is 1:1 with a higher insertion loss. In Figure 5(b), the specimens with a 25-mm thickness show a better acoustic performance. In Figure 5(c), the fine size of wood particles shows more stable results than the coarse ones. Above 1600 Hz, sound energy would dissipate significantly, which can be neglected in noise control. Based on the present results, we selected the design parameters as: 25 mm thickness, 1:1 wood and rubber particles and fine size wood particles (diameter 1–2 mm).

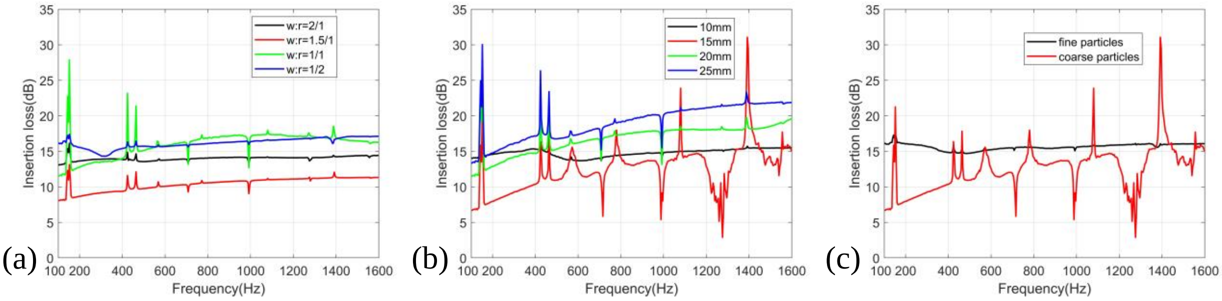

Figure 5. Insertion loss of recycled composite material samples with different factors: (a) weighting ratio of wood and rubber particles; (b) thickness of samples; and (c) size of wood particles

3.2 Acoustic PVDF thin-film speaker frequency responses

To investigate the acoustic characteristic of PVDF thin-film speaker [26, 27], (i) the steady-state response (SSR) and harmonic distortion (HD) of the speaker; (ii) the relationship between SPL responses and input signals are presented in Figure 6. In audio systems, a lower distortion refers to more stable reproduction of audio signals, implying less unintentional interference. As a secondary source for active control, the PVDF thin-film speaker was designed at a low-frequency range from 50 to 4000 Hz. In Figure 6(a), the frequency response (red line) shows a rising trend at low frequencies (lower than 800 Hz), while a flat trend occurs above 1500 Hz. In Figure 6(b), the responses indicate a stable stage above 2V (peak-to-peak) input signal. Hence, the input audio signal of the dual-function barrier test is selected as 2V (peak-to-peak). In addition, the targeted frequency bandwidth of this dual-function noise barrier test is above 800 Hz as a turning point, see Figure 6(a).

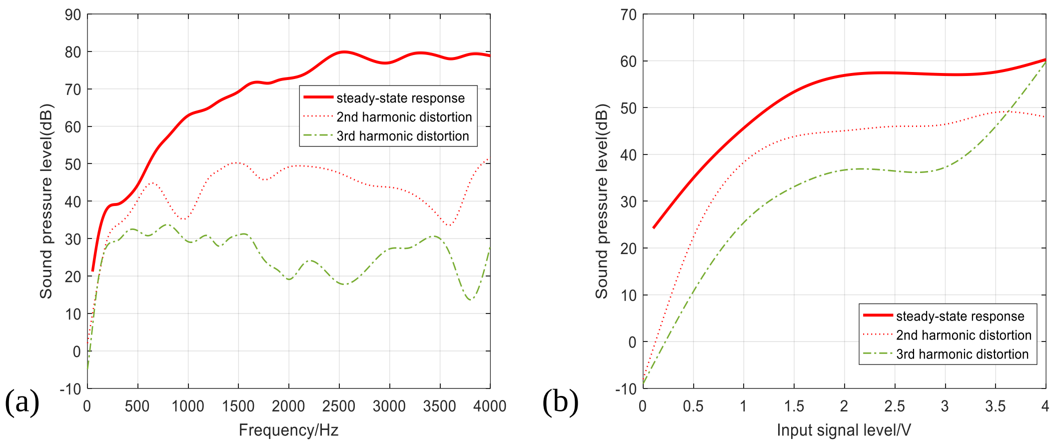

Figure 6. PVDF thin-film speaker acoustic characteristic test: (a) steady-state responses and harmonic distortions, and (b) input signals and harmonic distortion levels.

3.3 A scale-down model test for dual active and passive noise control

<u>3.3.1 Comparison of SPL and insertion loss</u>

To investigate the attenuation effect of a dual-function noise barrier, three different cases (i.e. without any barrier, with only the passive barrier, and with the dual-function noise barrier) are presented in Figure 7. In addition, the insertion loss results based on the SPL difference are shown in Figure 8. The frequency bandwidth is from 800 to 1500 Hz, in accordance with the frequency response analysis of PVDF thin-film speaker and acoustic material tests. From the overall attenuation trend, the sound insulation properties of the passive barrier perform better at higher frequencies.

In Figure 7, the black line represents the SPL without any barrier between the sound source and the receiver. It is in the range of 80 to 85 dB at the frequency bandwidth from 800 to 1500 Hz. The green line shows that the SPL is down to 70 dB in the presence of the passive barrier. The red line indicates a further decrease in the presence of the dual-function noise barrier. The PVDF thin-film speaker can achieve 3–5 dB (an average reduction is about 2.22 dB in the range of 1000−1500Hz) in noise reduction within the measurement space. In Figure 8, the insertion loss results, with active and passive control, show a better performance from 1100–1500 Hz. Minor deviated results may be due to the interference effect.

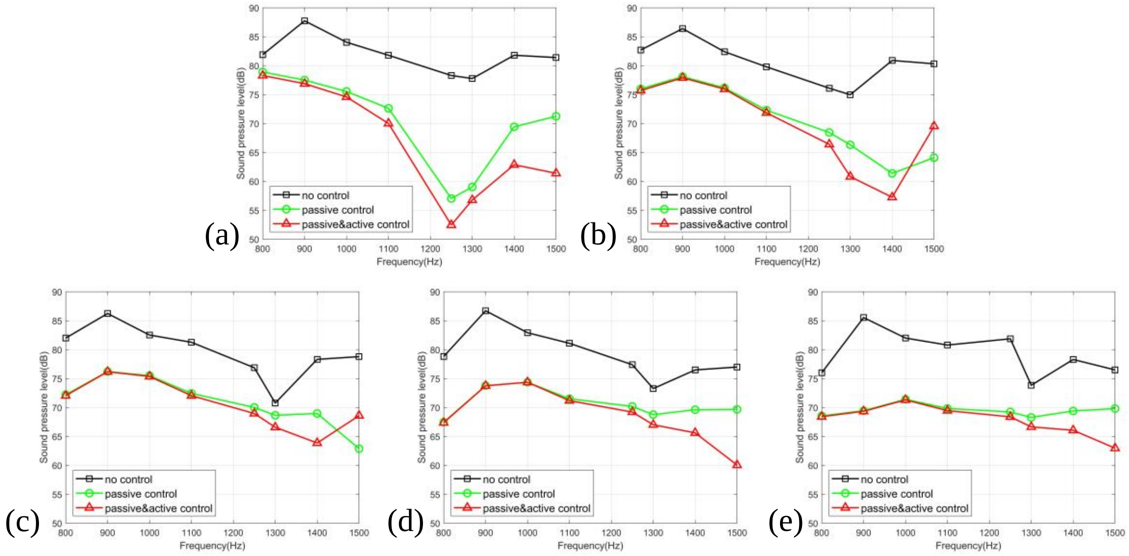

Figure 7. Sound pressure levels under three various conditions at different separation distance between sound barrier and four-microphone array: (a) 50 cm, (b)70 cm, (c) 90 cm, (d)110 cm, and (e) 130 cm.

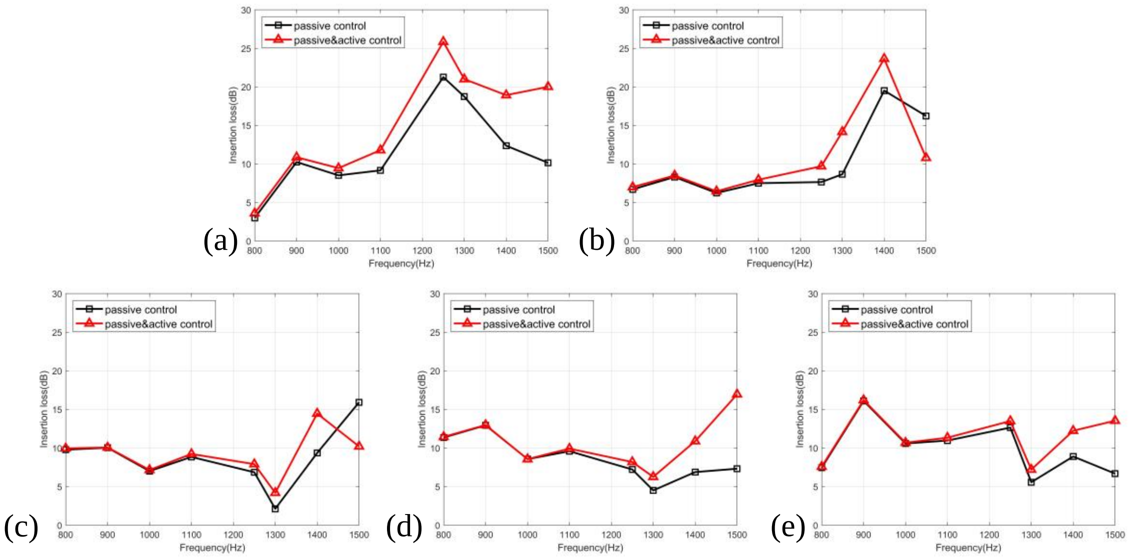

Figure 8. Insertion loss results under three various conditions at different separation distance between sound barrier and four-microphone array: (a) 50 cm, (b)70 cm, (c) 90 cm, (d)110 cm, and (e) 130 cm.

3.3.2 Contour map of SPL distribution and the trend of insertion loss

As we assume the noise barrier can be extended infinitely in the length direction, the SPL distribution can be neglected in the scale-down model. To evaluate the noise attenuation performance in a 2D profile between separation distance and height, contour maps are plotted along the centre axis of the hybrid barrier at 1250 and 1400 Hz, as shown in Figures 9 and 10. Two important metrics that can affect the SPL distribution in free fields are the separation distance and frequency range. Indeed, a wider frequency bandwidth for noise control can be realized by the dual-function noise barrier. Although we observe a lower SPL at the separation distance of 50 cm in the presence of active control, the effect of constructive interference may occur at 120 and 130 cm, see Figure 9(c). Nevertheless, the overall SPL reduction of the dual function noise barrier is about 12−14 dB, as shown in Fig. 11. In general, the SPL reduction can be accomplished over 10 dB using the passive barrier only. A further attenuation of 3−5 dB can be resulted in the presence of active control, but a small part of measurement space shall be compromised.

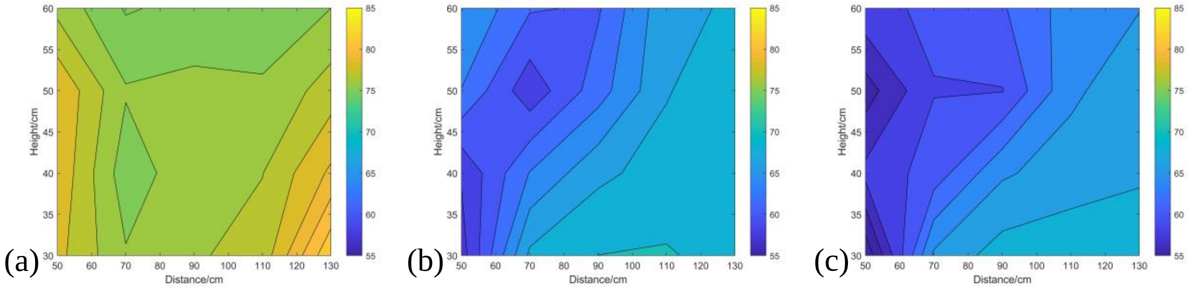

Figure 9. Contour profiles of SPL distribution under three cases (a) without any barrier, (b) with the passive barrier only; and (c) with the dual-function noise barrier at1250Hz.

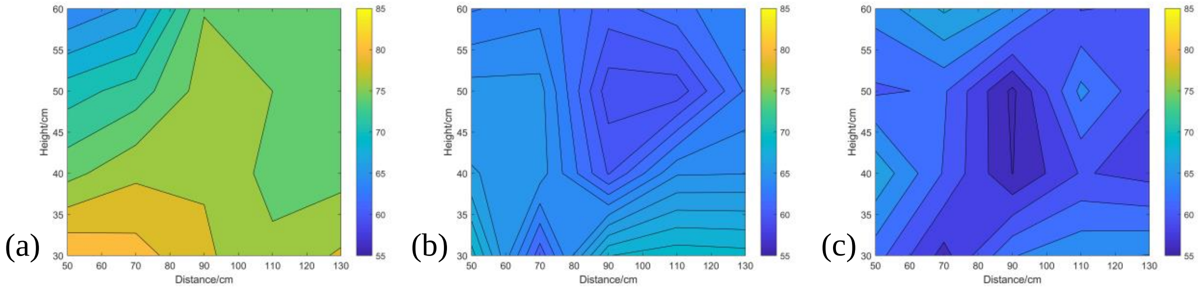

Figure 10. Contour profiles of SPL distribution under three cases: (a) without any barrier, (b) with the passive barrier only; and (c) with the dual-function noise barrier at 1400Hz.

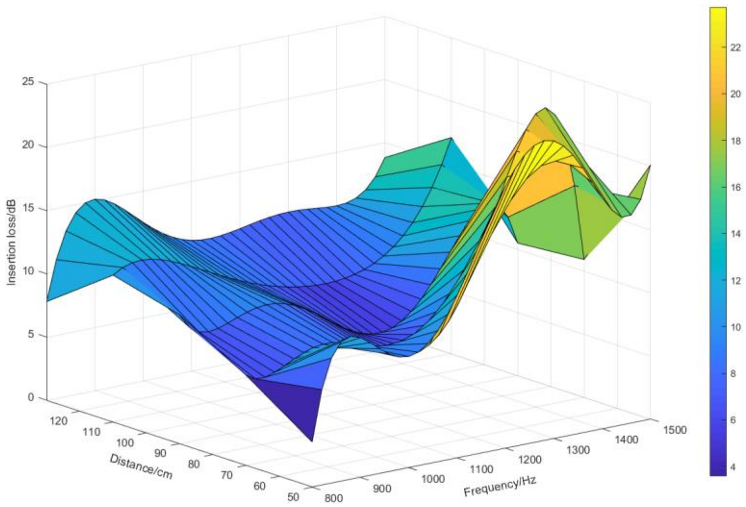

Figure 11. Variation of insertion loss of the dual-function noise barrier.

4. Conclusions

In this work, a dual-function noise barrier for active and passive control is proposed and tested. Only one PVDF thin-film material is required to realize active control. In the overall performance analysis, the insertion loss of the dual-function noise barrier is about 12−14 dB. In addition, PVDF, having lightweight, thin-film and flexible properties, shows great potentials in practical applications for active noise control, and it is easy to deploy on passive barriers. Moreover, such a barrier, as a retractable and movable noise mitigation device, is easy for installation and removal. However, the control technique needs to be further investigated to achieve stable frequency responses of PVDF thin-film speakers with a lower harmonic distortion at low frequencies. To enhance the effectiveness of noise control, optimizing the configuration of this dual-function noise barrier, especially the modification of the secondary source, is another on-going task.

5. Acknowledgement

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