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Hybrid active and passive noise control in ventilation duct with internally placed microphones module

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ABSTRACT

A feedforward active noise control (ANC) system combined with the passive silencer is built to reduce the acoustic noise propagating through the ventilation duct. The passive silencer consists of two layers which are made of aluminum plate and the perforated panels respectively, the cavity between the two layers is filled with the melamine foam. To overcome the two issues encountered in the active noise control for ventilation duct, i.e., the turbulent flow noise and the acoustic feedback, the emphasis of ANC system is the internally placed microphones module. The module is made of a perforated panel shell filled with the melamine foam, the reference and error microphones are both placed in the melamine foam. The real experiments show that the passive silencer has more than 20 dB noise attenuation at frequencies above 600 Hz, ANC can obtain more than 10 dB noise attenuation from 70 Hz to 200 Hz (the maximum 17 dB at 150 Hz) when the wind speed increases from 5 m/s to 10 m/s. In addition, the module is easy to install and maintain, and its manufacturing cost is also acceptable.

1. Introduction

In many modern environments such as the hotel and office, the ventilation is handled by a mechanical ventilation duct system, which often generates the broadband noise due to the fan and motor. The noise propagates along the duct, radiates into the room at the outlet and annoys the occupiers [1–4]. The passive silencer is often used to effectively attenuate the high frequency noise but tends to be relatively large and bulky for control the low frequency noise. One method to improve the low frequency noise attenuation in the duct with acceptable size and weight is active noise control (ANC) [5–8]. The single channel feedforward ANC system is often used in the ventilation duct system due to its good stability and noise attenuation performance, it comprises an upstream microphone (reference microphone) to detect the noise propagating in the duct and generate a reference signal for the ANC controller that steers a loudspeaker (secondary source), a downstream microphone (error microphone) to monitor the residual noise and let the controller adjust itself to minimise the residual noise [9–11].

However, adequate attenuation of the ANC system in the ventilation duct is difficult if the following two issues are not solved. The first issue is the turbulent flow noise, i.e., both the reference microphone and error microphone sense the sound propagating through the duct as well as the turbulent flow noise generated by the airflow around the microphones [3]. The turbulent flow noise reduces the coherence between the reference microphone and the error microphone, results in degraded performance of the feedforward ANC system. Several microphone installation methods are presented to reduce the influence of the turbulent flow noise, such as the windscreen [12,13], the probe tube [14], and outer microphone cavity [3]; The second issue is acoustic feedback, i.e., the secondary signal generated by the loudspeaker will travel upstream to the reference microphone, it may lead to the performance degradation and stability problems of the feedforward system [3,4,7,10]. There were mainly two kinds of methods to mitigate the acoustic feedback, one is by the adaptive algorithm, such as the feedback neutralization algorithm [10] and the robust controller design methods [15,16], the other is by acoustic arrangements, such as the dual reference microphones sensing [17], particular secondary loudspeakers [4,18] and the passive silencer [3].

Considering the ease of applying ANC in the practical ventilation duct, there may be some shortcomings in the above methods, for instance, if the microphones are installed with the probe tube inside the duct, the location inside the duct brings difficulties to the accessibility and maintenance of the microphone setup. If the microphones are installed in the cavity outside the duct and connected to the inside of the duct through a small slit on the duct [3], certainly it is easy for maintenance and to protect the microphone from air pollution and moisture, but milling the slit and

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mounting the cavity requires new manufacturing processes and may damage the original structure, these are negative to integrate the ANC system into the ventilation system.

In this paper, a hybrid active and passive noise control system is built for the ventilation duct system, where the passive silencer is designed to attenuate high frequency noise, the feedforward ANC system is integrated into the passive silencer to further reduce the low frequency noise. The emphasis is the design of the internally placed microphones module by taking three practical requests into consideration, the first is that the module should solve the above two issues to ensure the good ANC performance; the second is that the module can not damage the original duct and is easy to install and maintain; the third is that the module should not increase the manufacturing cost too much and be convenient for tuning the position of the reference and error microphones in field.

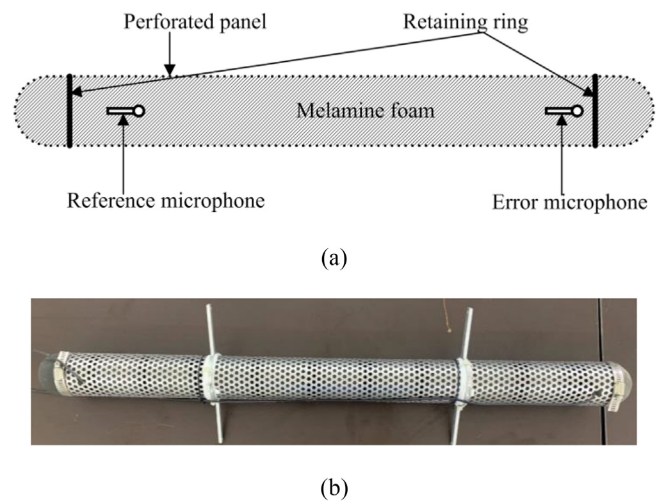


Fig. 2. The schematic diagram (a) and the actual photo (b) of the internally placed microphones module.

2. The hybrid active and passive noise control system for the ventilation duct

2.1. The passive silencer

Fig. 1 shows the longitudinal and cross section of the hybrid active and passive noise control system for the ventilation duct which includes the passive silencer and the internally placed microphones module. The passive silencer mainly adopts the design of resistance silencing and consists of two layers, the length of the passive silencer is about 1000 mm. The outer layer is made of aluminum plate and its width and height are 360 mm and 250 mm respectively. The inner layer is built with the perforated panels and its width and height are 200 mm and 100 mm respectively. The melamine foam is filled in the cavity between the two layers, which is a type of sound absorption, environmental protection and fire protection material. A secondary source (loudspeaker) is installed near the outlet of the passive silencer for active noise control.

2.2. The internally placed microphones module

Fig. 2 illustrates the internally placed microphones module, its length is about 700 mm and the diameter of the cross section is about 60 mm. Its shell is made of the perforated panels and consists of three segments, the middle segment is cylindrical and the other two segments are approximately hemispherical which are connected with the middle segment using the retaining ring and screws. The inside of the shell is fully filled with the melamine foam, and the reference and error microphones are both placed in the melamine foam.

The module is deliberately divided into three segments for ease of installation and maintenance, for example, when the end segments are disassembled, it is very convenient to tune the position of reference and error microphones in field, it is also easy to increase or decrease the amount of the filled melamine foam. The materials used to build this module are common and less expensive, also the manufacturing process is not complicated, so the cost of this module is completely acceptable from the viewpoint of practical application. As shown in Fig. 1, the module is fixed inside the passive silencer only using the two metal supports and some screws, so the module does not destroy the original structure of the passive silencer and is easy to install and maintain.

The reference and error microphones are hidden in the melamine foam, which is similar to be protected by a large size windscreen, in addition, the perforated panel shell can further reduce the air flow speed around the microphones, thus this module is expected to eliminate the influence of the turbulent flow noise and enhance the coherence between the reference microphone and the error microphone when the wind is flowing. On the other hand, when the sound emitted by the secondary source travels upstream, it will be attenuated by the passive silencer firstly, then further be attenuated by the module due to the absorption of the perforated panel shell and the melamine foam, hence the acoustic

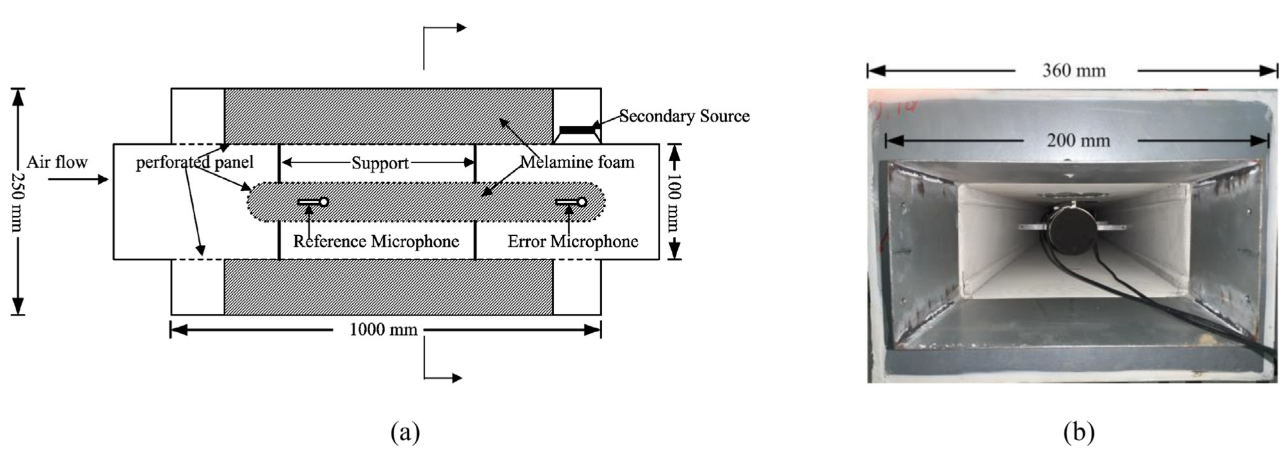


Fig. 1. The longitudinal section (a) and cross section (b) view of the hybrid active and passive noise control system for the ventilation duct.

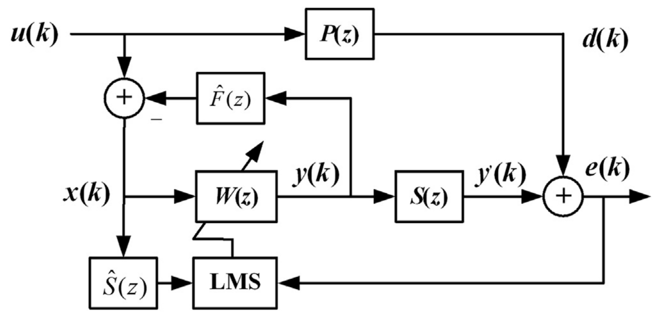


Fig. 3. The block diagram of the single channel feedforward ANC system using the FxLMS algorithm with acoustic feedback neutralization.

feedback may be suppressed by this module. In brief, the turbulent flow noise and acoustic feedback issues can be solved to ensure the good ANC performance via this module.

The main body of the passive silencer is about 1000 mm long in Fig. 1, the internally placed microphones module is about 700 mm long. The location of the error microphone is close to the outlet of the passive silencer and is nearly in front of the secondary source; the reference microphone is close to the upstream of the passive silencer, the distance between the reference microphone and the error microphone is about 500 mm, so the acoustic delay from the reference microphone to the error microphone is about 500 (mm)/340 (m/s)≈1.47 ms, the electrical delay of the ANC controller is less than 0.2 ms with 10000 Hz sampling rate, so the ANC system is a really feedforward system.

2.3. The filtered-x least mean square algorithm with acoustic feedback neutralization

Fig. 3 is the block diagram of the single channel feedforward ANC system using the filtered-x least mean square (FxLMS) algorithm with acoustic feedback neutralization (FxLMS-AFN) [10]. It includes: an error microphone to measure the residual noise $e(k)$, a reference microphone to obtain the reference signal $u(k)$; a secondary sound source to generate the canceling signal $y(k)$ for attenuation of the primary noise $d(k)$; the primary path, the secondary path, the estimated secondary path and the estimated acoustic feedback path is denoted by $P(z)$, $S(z)$, $\hat{S}(z)$ and $\hat{F}(z)$ respectively; the control filter $W(z)$ is an L taps finite impulse response (FIR) filter, i.e., $\mathbf{w}(k) = [w_0(k), w_1(k),\ldots w_{L-1}(k)]^T$.

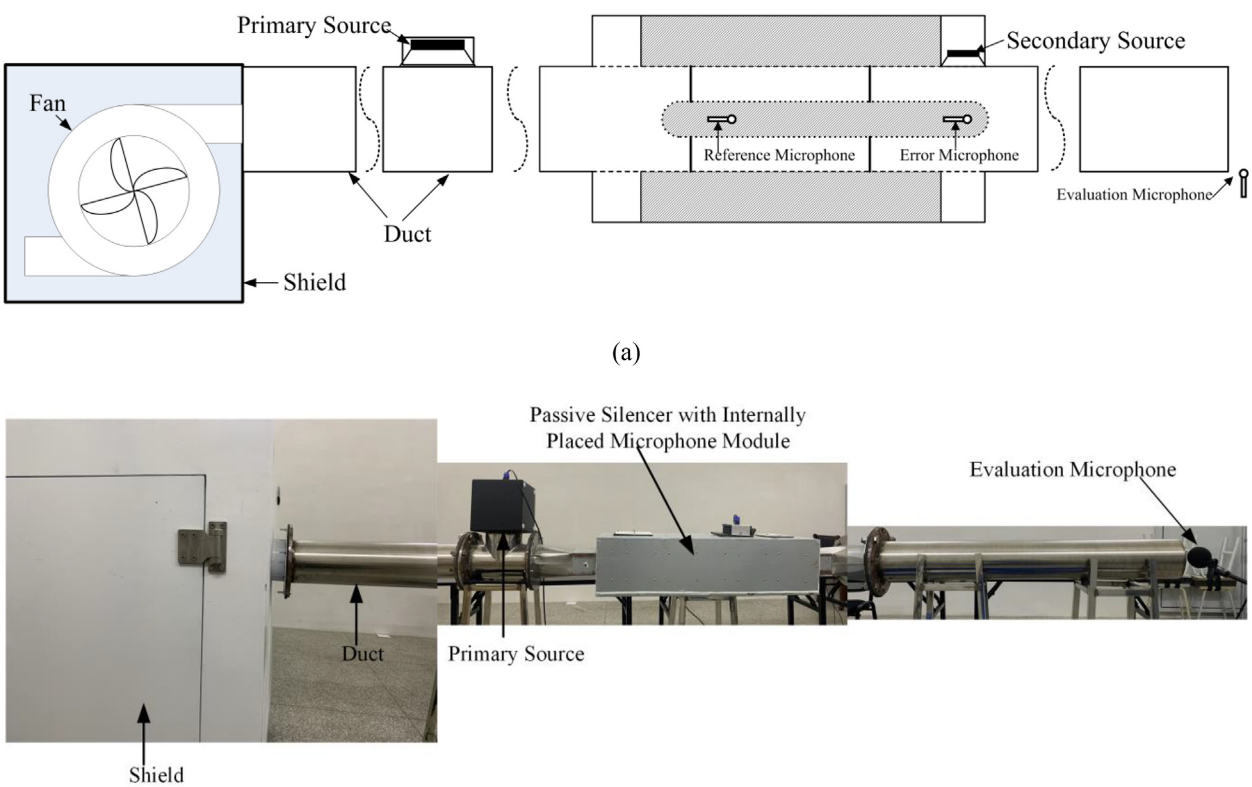
Here the feedback neutralized reference signal $x(k)$ is obtained by subtracting the estimated acoustic feedback from $u(k)$, i.e.,

$$x(k) = u(k) - y(k) * \hat{f}(k) \quad (1)$$

$\hat{f}(k)$ is the time domain impulse response of $\hat{F}(z)$ and "*" means the linear convolution. Then the update equation for $\mathbf{w}(k)$ by using $x(k)$ becomes

$$\mathbf{w}(k+1) = \mathbf{w}(k) - \mu e(k)\mathbf{x}'(k) \quad (2)$$

where μ is the step-size and $\mathbf{x}'(k)$ is the filtered reference signal vector which element is the linear convolution of $x(k)$ and the time domain impulse response of $\hat{S}(z)$.



(a)

(b)

Fig. 4. The experimental setup of the hybrid active and passive noise control system for the ventilation duct, (a) the schematic diagram and (b) the actual photo.

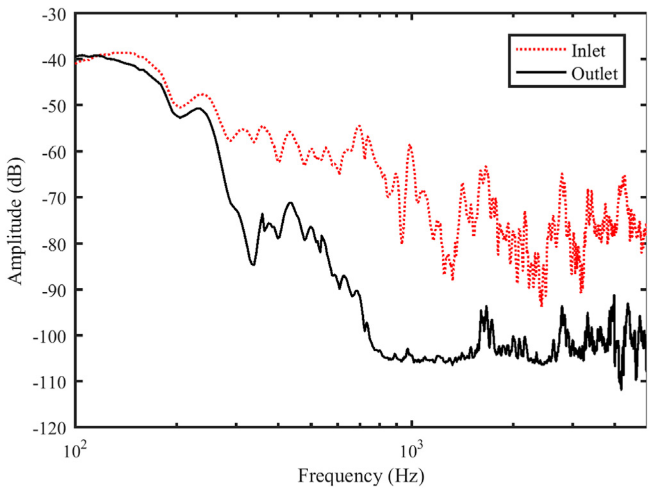


Fig. 5. The power spectral density curves of the signals captured at the inlet and outlet of the passive silencer.

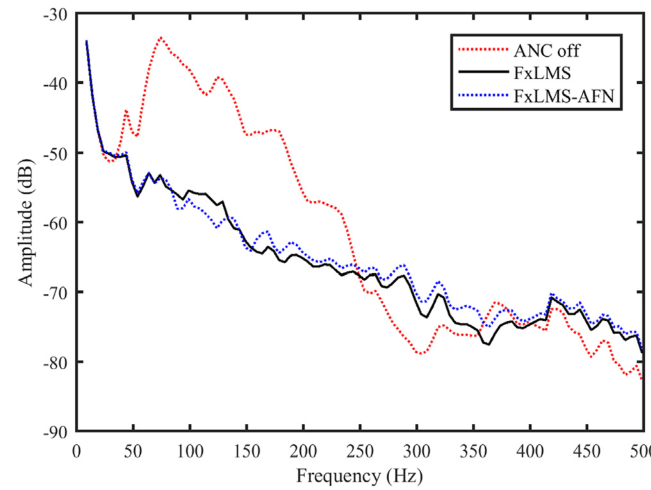


Fig. 7. The power spectral density curves of the signals captured at the error microphone under the conditions: ANC off, the FxLMS and FxLMS-AFN algorithms.

3. Experiments and discussions

Experiments were carried out to examine the performance of the hybrid active and passive noise control system for the ventilation duct. Fig. 4 illustrates the experimental setup, where the fan is fixed in the acoustic shield to reduce the influence of the vibration and direct sound emission on the performance test. When the fan is on, the wind flows, as well as the noise propagates along the duct. In order to compare the performance of the hybrid active and passive noise control system under the "wind" (the fan is on) and "without wind" (the fan is off) conditions, a primary source (loudspeaker) is installed between the outlet of the acoustic shield and the inlet of the passive silencer. The sampling frequency of the ANC system is 10000 Hz, and the ANC controller is implemented on a field programmable gate array.

The noise attenuation performance of the passive silencer is measured by using two calibrated microphones located at the inlet and outlet of the passive silencer respectively, the white noise is played with the primary source and the power spectral density (PSD) curves of the two microphone signals are shown in Fig. 5. It is found that the passive silencer has effective noise attenuation at high frequencies, especially above 600 Hz, more than 20 dB

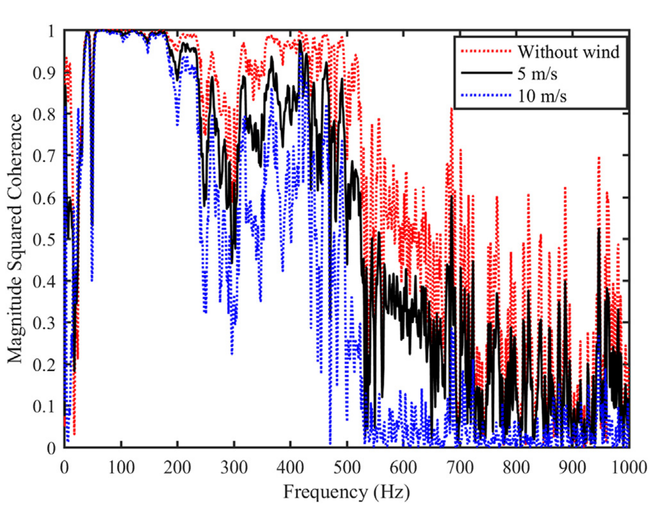
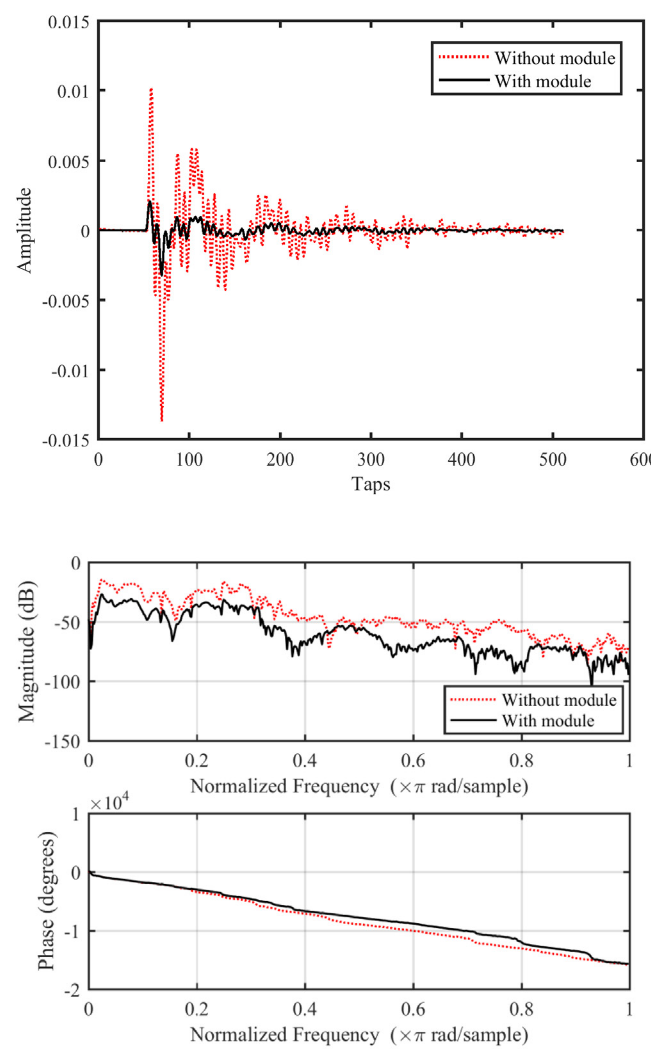


Fig. 6. The magnitude squared coherence between the reference signal and the error signal under "without wind", wind speed is 5 m/s and 10 m/s conditions.



(b)

Fig. 8. The estimated feedback paths under "Without module" and "With module" conditions: (a) impulse response, (b) frequency response.

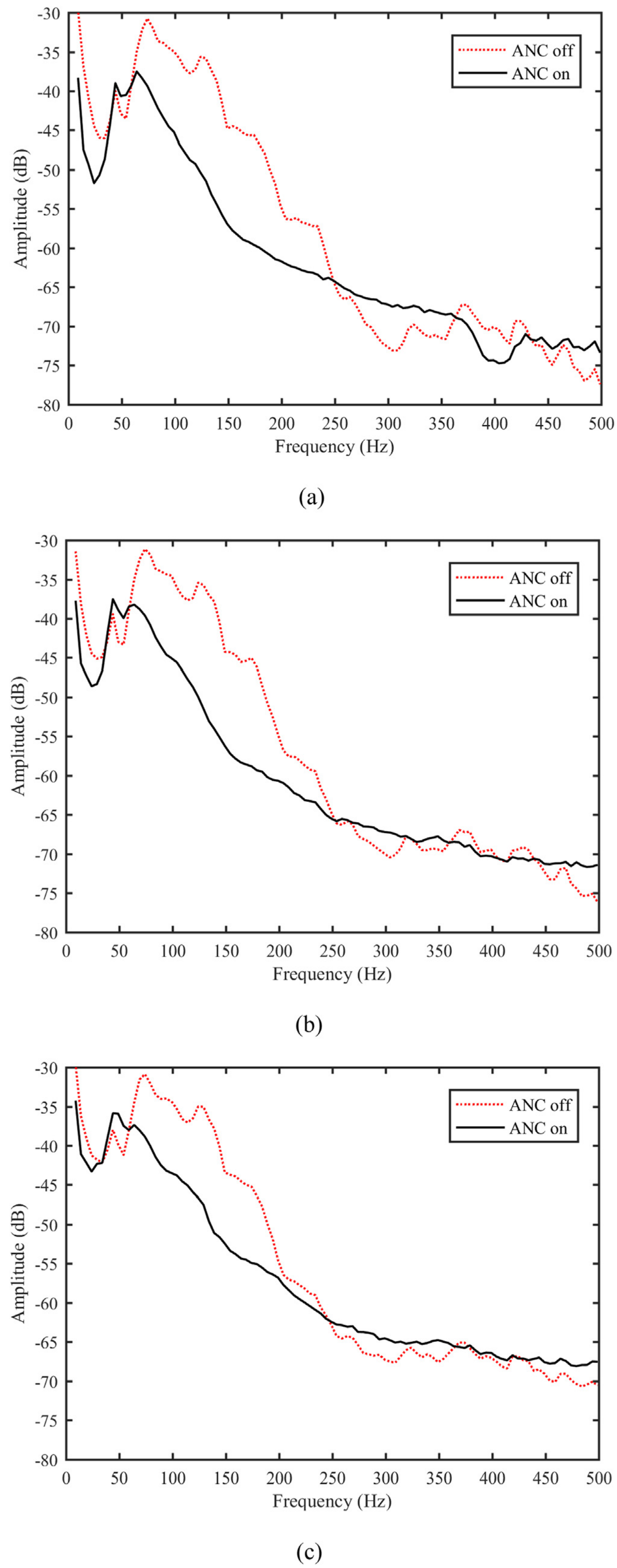


Fig. 9. The power spectral density of the sound measured at the outlet of the duct with ANC off and ANC on under three wind speeds: (a) 5 m/s, (b) 10 m/s, (c) 15 m/s.

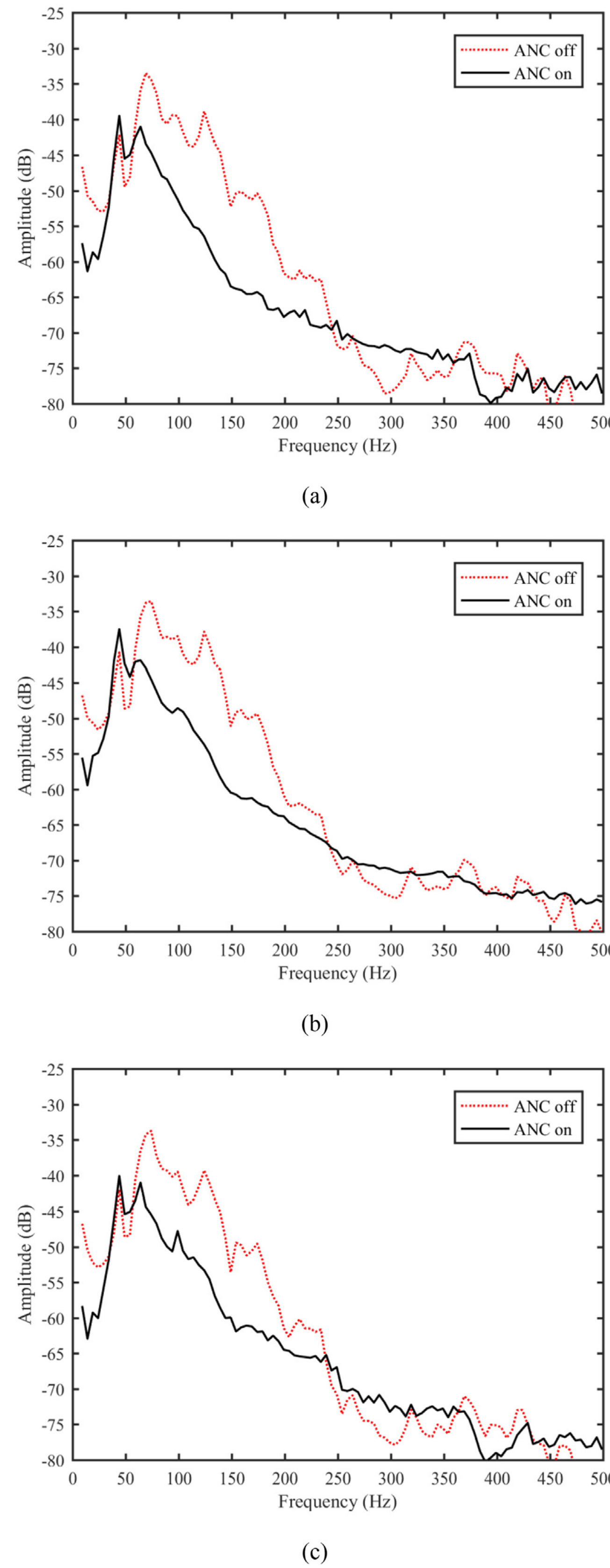


Fig. 10. The power spectral density of the sound measured outside the duct (about 2 m away from the outlet of the duct): (a) 5 m/s wind speed, (b) 10 m/s wind speed, (c) 15 m/s wind speed.

attenuation is achieved, but the noise attenuation from 100 Hz to 300 Hz is less than 5 dB, thus there is a need to further reduce the low frequency noise via active control.

In order to investigate whether the internally placed microphones module can eliminate the effect of the turbulent flow noise on the reference and error microphones, the signals of the reference and error microphones are recorded simultaneously under three conditions: "Without wind", the wind speed is 5 m/s and the wind speed is 10 m/s. For all the three conditions, the white noise is played using the primary source. Then the magnitude squared coherence between the reference signal and the error signal are plotted in Fig. 6, where "Without wind" means that the fan is off and there is no wind in the duct, "5 m/s" and "10 m/s" mean that the fan is on and tuned to make the wind speed in the duct is 5 m/s and 10 m/s respectively. The magnitude squared coherence is a function of frequency with values between 0 and 1, which indicates how well the reference signal $u(k)$ is coherent to error signal $e(k)$ at each frequency. Eq. (3) is the definition of the magnitude squared coherence (here f denotes the frequency), it is a function of the power spectral densities of $u(k)$ and $e(k)$ ($P_{uu}(f)$, $P_{ee}(f)$), and the cross power spectral density of $u(k)$ and $e(k)$ ($P_{ue}(f)$):

$$C_{ue}(f) = \frac{|P_{ue}(f)|^2}{P_{uu}(f)P_{ee}(f)} \tag{3}$$

It is found in Fig. 6 that when the wind speed increases, the coherence between the reference signal and the error signal above 250 Hz drops very clearly, but if zoomed in to the 50–150 Hz and 150 Hz–200 Hz frequency band, the coherence between the reference signal and the error signal is still larger than 0.99 and 0.9 respectively. It is known that the coherence can give a simple measure to estimate the maximum noise reduction of an ANC system [10], if the coherence is 0.99 or 0.9 at some frequency, a maximum of 20 dB or 10 dB attenuation can be obtained. Therefore, it is confirmed that the influence of the turbulent flow noise at low frequency band can be mitigated by the internally placed microphones module.

Experiments are carried out to verify the ability of the internally placed microphones module to reduce the acoustic feedback, where the white noise is played with the primary source, the ANC performance is tested using the FxLMS-AFN (shown in Fig. 3 and the FxLMS algorithms respectively. The PSD curves of the error microphone signal with "ANC off", the FxLMS-AFN and the FxLMS algorithms are shown in Fig. 7. It is shown that the curves of the "FxLMS" and "FxLMS-AFN" algorithms are very close and 10–20 dB noise reduction can be achieved from 50 Hz to 250 Hz frequency band. The results indicate that the FxLMS algorithm can be used directly in the hybrid active and passive noise control system for the ventilation duct via the internally placed microphones module if the computation ability of the ANC controller is limited.

The reason that the internally placed microphones module with the passive silencer can reduce the acoustic feedback is demonstrated in Fig. 8, where the feedback paths $\hat{F}(z)$ in Fig. 3 are estimated under two conditions "Without module" and "With module". "With module" means that the internally placed microphones module is installed in the passive silencer as shown in Fig. 1, "Without module" means that the reference and error microphones are installed in the passive silencer directly but without the protection of the perforated panels and melamine foam. It is evident that $\hat{F}(z)$ amplitude of "With module" is smaller than that of "Without module" and the effect of the acoustic feedback may be neglected if the module is used. It has been reported that the passive silencer can partly reduce the acoustic feedback in the ventilation duct, because it can be found from Fig. 1 that when the secondary signal emitted by the secondary source propagates upstream to the reference microphone, the secondary signal will be absorbed due to the existence of the perforated panels and melamine foam [3]. The internally placed microphones module can further reduce the acoustic feedback because the reference microphone is installed inside the perforated panels and melamine foam.

The ANC performance using internally placed microphones module is tested with three different wind speeds: 5 m/s, 10 m/s and 15 m/s, the FxLMS-AFN algorithm is employed in the ANC controller. The signal of the evaluation microphone at the outlet of the duct is firstly used to evaluate the ANC performance, as shown in Fig. 4, a segment of duct (about 1200 mm long) is connected to the outlet of the passive silencer, and the evaluation microphone is located near the outlet of the duct. The PSD curves with ANC off and ANC on are illustrated in Fig. 9. The controller filter is a 1500 taps finite impulse response (FIR) filter, the estimated secondary path and the feedback path is modeled with 512 taps FIR filter.

Fig. 9 (a) (b) show that when the wind speed increases from 5 m/s to 10 m/s, the ANC performance in the 70–200 Hz frequency band are very closely, the maximum 17 dB noise attenuation is achieved at about 150 Hz and more than 10 dB noise attenuation is achieved from 70 Hz to 200 Hz. But from 200 Hz to 250 Hz, the noise attenuation with 10 m/s wind speed is about 3 dB lower than that with 5 m/s wind speed.

Fig. 9 (c) shows that when the wind speed further increases to 15 m/s, the ANC performance degrades in comparison with that in Fig. 9 (a), from 70 Hz to 250 Hz, the noise attenuation with 15 m/s wind speed is about 4–5 dB lower than that with 5 m/s speed, the maximum 13 dB noise attenuation is achieved at about 150 Hz and from 200 Hz to 250 Hz, the noise attenuation is less than 2 dB, so the effective frequency band is 70–200 Hz, which is narrower than that (70–250 Hz) in Fig. 9 (a).

Finally, the ANC performance is evaluated by locating the evaluation microphone outside the duct (about 2 m away from the outlet of the duct), the results are shown in Fig. 10. It can be found that the tendency from Fig. 10 (a) to Fig. 10 (c) is similar to that in Fig. 9. When the wind speed increases from 5 m/s to 15 m/s, the ANC performance degrades, i.e., the noise attenuation becomes smaller and the effective frequency band of noise attenuation becomes narrower.

4. Conclusions

This paper presents a hybrid passive and active noise control system to attenuate the acoustic noise propagating through the ventilation ducts. The passive part employs the design of resistance silencer and includes two layers built by the aluminum plate and perforated plate respectively, the room between the two layers is filled with melamine foam. The active part is a feedforward active noise control system and its focus is the design of the internally placed microphones module to solve the turbulent flow noise and the acoustic feedback problems, the internally placed microphones module is made of a perforated panels shell filled with the melamine foam, then the reference and error microphones are both fixed in the melamine foam. The module is less expensive, easy to install and maintain. The real experiments show that more than 20 dB noise attenuation at frequencies above 600 Hz is obtained by using the passive silencer; 10 dB noise attenuation from 70 Hz to 200 Hz with the maximum 17 dB at 150 Hz is achieved by the active control when the wind speed increases from 5 m/s to 10 m/s. A problem worthy of further work is to investigate the fan noise component (such as the periodic component and the turbulent component etc.) and design more effective passive and active control system.

CRediT authorship contribution statement

Lifu Wu: Conceptualization, Funding acquisition, Methodology, Project administration, Writing – original draft, Writing – review & editing. **Lei Wang:** Formal analysis, Resources. **Shuaiheng Sun:** Software. **Xinnian Sun:** Validation, Visualization.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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References

[1] Gardonio P, Rohlfing J. Modular feed-forward active noise control units for ventilation ducts. J Acoust Soc Am 2014;136(6):3051–62.
[2] Rohlfing J, Gardonio P. Ventilation duct with concurrent acoustic feed-forward and decentralised structural feedback active control. J Sound Vib 2014;333(3):630–45.
[3] Larsson M, Johansson S, Claesson I, Hakansson L. A module based active noise control system for ventilation systems, Part II: performance evaluation. Int J Acoust Vibr 2009;14(4):196–206.
[4] Kobayashi Y, Fujioka H. Active noise cancellation for ventilation ducts using a pair of loudspeakers by sampled-Data H_∞ optimization. Adv Acoust Vib 2008;2008:1–8.
[5] Kato M. Active noise control in a duct by an analog neural network circuit. Appl Acoust 2011;72(10):732–6.
[6] Jones RW, Olsen BL, Mace BR. Comparison of convergence characteristics of adaptive IIR and FIR filters for active noise control in a duct. Appl Acoust 2007;68(7):729–38.
[7] Romeu J, Salueña X, Jiménez S, Capdevila R, Coll Ll. Active noise control in ducts in presence of standing waves, Its influence on feedback effect. Appl Acoust 2001;62(1):3–14.
[8] Chen K-T, Chen YH, Hsueh WJ, Wang JN, Liu YH. The study of an adaptively active control on the acoustic propagation in a pipe. Appl Acoust 1998;55(1):53–66.
[9] Hansen C, Snyder S, Qiu X, Brooks L, Moreau D. Active control of noise and vibration. Second Ed. CRC Press; 2013.
[10] Kuo SM, Morgan DR. Active noise control systems: algorithms and DSP implementations. New York: Wiley; 1996.
[11] Elliott SJ. Signal processing for active control. London (UK): Academic Press; 2001.
[12] Beranek L. Noise and vibration control. Inc.: McGraw Hill; 1988.
[13] Shepherd IC, La Fontaine RF. Microphone screens for acoustic measurement in turbulent flows. J Sound Vib 1986;111(1):153–65.
[14] Munjal ML, Eriksson LJ. An exact one-dimensional analysis of the acoustic sensitivity of the anti-turbulence probe tube in a duct. J Acous Soc Am 1989;85(2):582–7.
[15] An F, Cao Y, Wu M, Sun H, Liu B, Yang J. Robust Wiener controller design with acoustic feedback for active noise control systems. J Acoust Soc Am 2019;145(4):EL291–6.
[16] Bai MR, Chen H-Y, Yang L, Huang S-C. Active control of noise in a duct using the sparsely coded time-domain underdetermined multichannel inverse filters. J Acoust Soc Am 2019;146(2):1371–81.
[17] Takahashi M, Kuribayashi T, Asami K, et al. Electric sound cancellation in air-conditioning duct system. In: 1986 Inter-noise Conference Proceedings. p. 607–610.
[18] Prezelj J, Čudina M. A secondary source configuration for control of a ventilation fan noise in ducts. Strojniski Vestnik-J Mech Eng 2011;57(06):468–76.