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RECENT ADVANCES ON ACTIVE CONTROL OF SOUND TRANSMISSION THROUGH VENTILATION WINDOWS

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Windows are often the weakest part in a building in terms of sound transmission loss from outside. Many researchers have applied active noise control to improve the sound transmission loss of windows, which includes distributing an array of loudspeakers on the opening of the windows, applying vibration actuators on the glasses of the windows, and putting loudspeakers in the gap of the double layered or plenum windows. This paper focuses on active control of sound transmission through windows which allow nature ventilation. Recent advances in 8 countries and areas in the last 5 years are summarised and compared first, then the limitations of current research, implementation issues and future directions are discussed.
Keywords: active control, ventilation windows, sound transmission

1. Introduction

There have been many attempts to develop suitable windows that have both good noise reduction performance and sufficient ventilation for providing fresh air. Early in 1973, Ford and Kerry investigated the effect of the opening area of windows on the sound reduction index and found that partially opened double glazing was 10 dBA better than partially opened single glazing and double glazing could be opened up to 100 mm to reach the noise insulation capacity of closed single glazing [1]. In 1998, Field and Fricke demonstrated that quarter wave resonators of different lengths can be used outside building ventilation openings to reduce noise entering buildings over a wide frequency range with an attenuation of about 7 dB in certain 1/3 octave bands [2].

In 2005, Kang and Brocklesby developed a staggered window system, where the opening sashes of a spaced double glazing window were staggered to create a natural ventilation path and prevent direct sound propagation and transparent microperforated absorbers were used along the ventilation path to attenuate external noise [3]. It was found that external noise could be efficiently reduced from 500 Hz to 8000 Hz; however, the performance of the staggered window system is not satisfactory at low frequencies. In 2009, Yuya et al. presented a model for soundproofing casement windows by optimising the locations of input and output openings as well as the input area size [4].

In 2013, Tong and Tang investigated the insertion losses of plenum windows installed on a building facade for a non-parallel line source with a 1:4 scaled down model in a semi-anechoic chamber, and found that the insertion losses were around 5-18 dB depending on different orientation situations [5]. Two years later, a full scale field measurement was carried out with two identical mock-up test rooms the same dimensions as those commonly adopted for Hong Kong public housing near a busy trunk road, one was equipped with plenum windows, while the other with the conventional side-hung casement windows. Four internal room settings were compared and the results show that the acoustical benefit achieved by replacing the side-hung casement windows with the plenum windows tested is around 7.1-9.5 dBA [6].

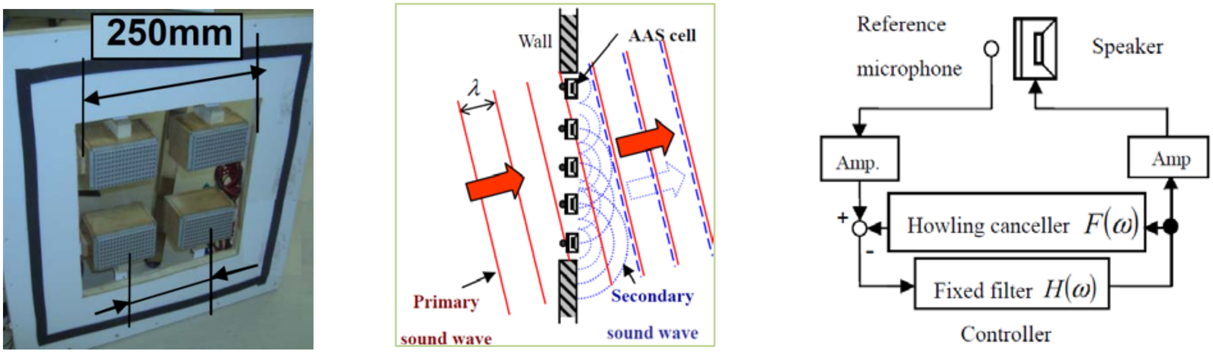
The sound insulation performance of passive windows is usually poor in the low frequency range. Active noise control (ANC) techniques have been proposed to solve the problem. In 2002, Zhang et al. proposed a model for examining the coherence between reference and error signals [7]. In 2005, Ise arranged 16 independent single channel ANC systems at an open window to reflect the incident external noise back and achieved more than 10 dB noise reduction at the error sensors in the frequency range from 200 Hz to 700 Hz [8]. In 2011, Qiu et al. reported the research progress on natural ventilation ANC windows at that time [9]. This paper summarises recent advances in the direction in the last 5 years, and discusses their limitations and future directions.

2. Recent advances

Many researchers in the world have been contributing to the research in the field. Only recent work in the following 8 countries and areas is introduced to illustrate the advances in the direction.

2.1 Japan

Professor Masaharu Nishimura and his team from Tottori University have been developing the Active Acoustic Shielding (AAS) system for nearly 10 years. From 2008, they reported their progress almost every year at Internoise Conferences [10]. The AAS system consists of a number of identical AAS cells in an array. Figure 1 shows a photo of a 4-cell AAS window, the basic concept of the AAS for sound transmission control through an open window, and a diagram of an AAS cell.



(a) (b) (c)

Figure 1: (a) Photo of a 4-cell AAS window. (b) Basic concept of the AAS. (c) Diagram of an AAS cell [10].

Each AAS cell is a simple feedfoward active control system with a reference microphone as close as possible in front of a secondary source. The control filter $H(\omega)$ is designed off line to cancel the sound in front of the cell, and a howling compensation filter $F(\omega)$ is adopted to reduce the acoustical feedback from the secondary source to the reference microphone. With nearly collocated reference microphone and secondary source, the same control filter is expected to control incident sound from different directions [11]. A small AAS window with a size of 250×250 mm^2 was manufactured with 4 AAS cells and installed in the door of an anechoic room, and the measurement results show that the AAS window can effectively reduce the random incident noise transmission in the frequency range from 500 Hz to 2000 Hz. The challenge is that large numbers of AAS cells are necessary for practical large windows, so new decentralized controllers and related algorithms need to be developed [12]. FPGA is being used to develop control hardware to reduce system latency.

2.2 Singapore

Two teams are carrying out research related to active control of sound transmission through ventilation windows in Singapore, both being funded by the Singapore Ministry of National Development and National Research Foundation. The team led by Dr. Woon Seng Gan from Nanyang Technological University (NTU) focuses on the development of multiple channel ANC systems for open windows, while the team led by Dr. Kui Yao from the Institute of Materials Research and Engineering

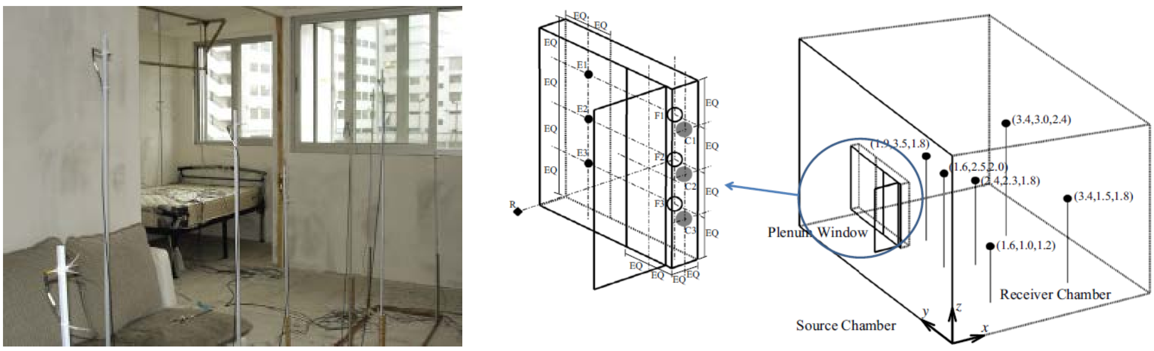
(IMRE), A*STAR, focuses more on the development of transparent piezoelectric film speakers and high performance porous material for ANC and passive noise mitigation [13-17]. Figure 2 shows a diagram of the selective ANC system for open windows using sound classification, an open window ANC system with 8 AAS cells built at NTU, and the transparent piezoelectric film speakers developed by IMRE for ANC. The NTU team, collaborating with Prof. Masaharu Nishimura from Japan and Prof. Steven Elliott from UK, has been spending significant amount of efforts on the implementation issues related to the decentralized multiple channel feedforward ANC algorithms of the AAS systems.

(a) (b) (c)

Figure 2: (a) Diagram of the selective ANC system for open window [13]. (b) The open window ANC system with 8 AAS cells [13]. (c) The transparent piezoelectric film speakers for ANC, 200 × 200 mm^2 [17].

2.3 Hong Kong

Professor Shiu-Keung Tang from the Hong Kong Polytechnic University reviewed recent progress in the research and development of natural ventilation enabling noise control devices for high-rise buildings in cities with serious traffic noise, and found that protrusive devices, such as balconies, lintels, and fins, are generally not effective due to city reverberation [18]. Plenum windows and other similar double-wall plenum structures with a staggered air inlet and outlet are found to be useful as natural ventilation enabling noise control devices. They adopted ANC to improve plenum windows' noise reduction [19]. A series of experiments was conducted to understand how the implementation of the ANC system would affect the sound transmission across a plenum window. In their 3 channel ANC experiments, the primary sound source was a 6-inch loudspeaker placed on the floor of the source chamber, and the secondary control loudspeakers were fixed close to the outdoor window opening. The effects of secondary control loudspeaker orientation relative to the plenum cavity and their locations and the reverberation in the receiver chamber on the performance of the active control were investigated. Figure 3 shows a photo of the furnished test room for full scale field tests of sound transmission across plenum windows and the experimental setup.



(a) (b)

Figure 3: (a) A photo of the furnished test room [6]. (b) The experimental setup •: error Microphones; ♦: reference microphone; ○ and ●: secondary control loudspeakers [19].

2.4 China

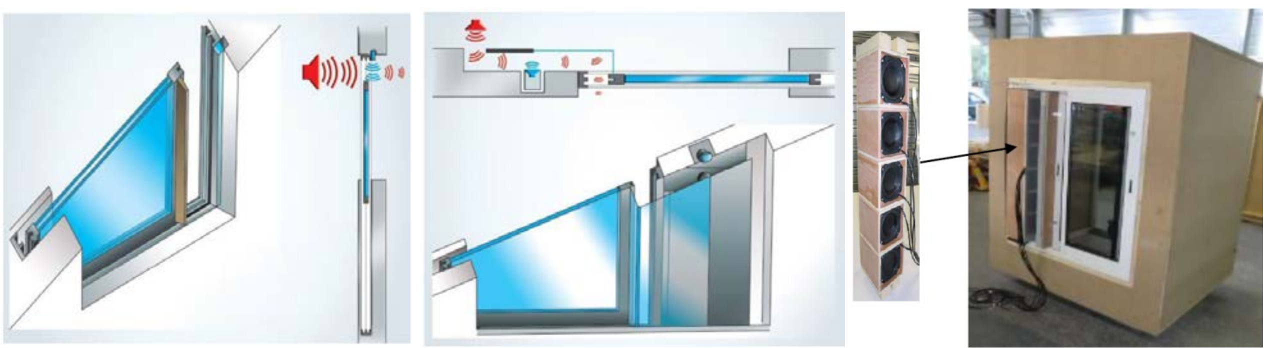
The team in Nanjing University started to investigate the feasibility of applying ANC techniques to plenum windows in 2010 [9]. Figure 4 shows photos of the experiment setup and the prototype they tested onsite [20]. The prototype window was installed in a glass room with a dimension of 2.0 m long, 2.5 m wide and 2.5 m high. The inside wall of the room is paved with a layer of sound absorption material to reduce the reverberation inside the room. The dimensions of whole casement window are 1.1 m wide and 0.6 m high, being divided into left, middle and right parts. The window consists of two layers of glass with a space of 0.1 m. The middle part cannot be opened, while the right and left parts can be opened in a staggered way to create a natural ventilation path. The middle window is divided into upper and lower parts, so that each part can be treated as a separate ventilation duct. Two separate single channel ANC systems were used in the window, where the reference microphone for each duct was at the inlet of the duct, while the control loudspeaker was located at the outlet of the duct. The error microphone is on the right wall of the window. Figure 4(c) shows the sound pressure level at the error microphones with and without ANC, where more than 12 dB broadband control was obtained with effective frequency up to 800 Hz.

(a) (b) (c)

Figure 4: (a) A photo of the experimental setup [20]. (b) A prototype natural ventilation ANC window. (c) The sound pressure level at the error microphones with ANC on (red solid line) or off (green dash line) [9].

2.5 France

TechnoFirst (a French company) partnered with the French Environment and Energy Management Agency (initiated in 2011) to develop an active double-glazed window with nature ventilation [21]. They investigated two configurations. For the first one, loudspeakers are integrated in the window frame to cancel the incidence sound through the opening directly, and the control is effective below 500 Hz. The second is an ANC plenum system with better noise reduction up to 1700 Hz. Figure 5 shows the diagrams of the Active Window and the Active Labyrinth configurations, and a photo of the test bench with the Active Window configuration.

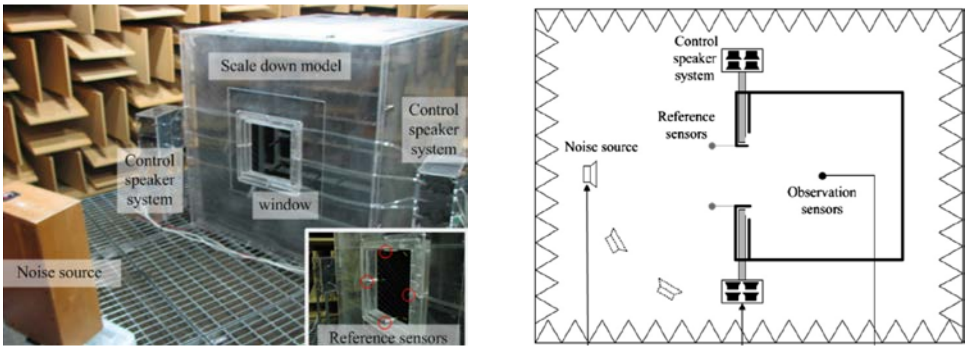


(a) (b) (c)

Figure 5: (a) A diagram of the Active Window configuration. (b) A diagram of the Active Labyrinth configuration. (c) A photo of the test bench with the Active Window configuration [21].

2.6 Republic of Korea

Professor Youngjin Park's team at the Korea Advanced Institute of Science and Technology (KAIST) proposed an ANC system for open windows without placing the sensors and control sources inside the interior space of the building [22]. The scale model experiments were carried out with a 0.3 × 0.3 m^2 open window installed in a scale room model of 1.45 × 1.2 × 1.2 m^3. Eight loudspeakers were placed outside the model and the cylindrical ducts ran from the loudspeakers to the control source locations, which were distributed evenly at the edge of the window as shown in Fig. 6(a). A sketch map of the system is shown Fig. 6(b). The system uses a feedforward control scheme which does not need error sensors for practicability. The control coefficients for the controller were calculated theoretically off line by using the Rayleigh integral equation and Green's function. The performance of the active window system was verified with directional exterior noise, where the direction of the incident sound was estimated by using receiving signals from the reference sensors. The results show that the proposed system can achieve an average noise reduction of up to 10 dB in the frequency band from 400 Hz to 1000 Hz.



(a) (b)

Figure 6: Experimental setup of the active window system: (a) photograph of the experimental setup, (b) a sketch map of the active noise control system [22].

2.7 Germany

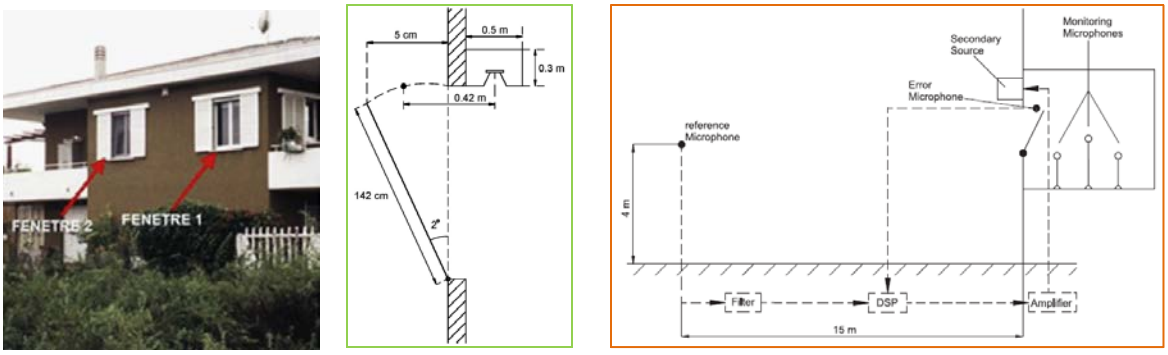
Professor Delf Sachau and his team in the Helmut Schmidt University of Germany carried out a joint industry project funded by the Deutsche Bundesstiftung Umwelt (DBU) to improve the quality of living and work by means of using an adaptive noise-blocker [23]. As shown in Fig.7, a multi-channel feedforward ANC system (1 reference sensor, 8 secondary sources and 14 error sensors) was used to block the noise transmission into the interior space through the opening of a tilted window. The window has dimensions of 0.91 × 0.91 m^2 and the primary source is a loudspeaker about 3 m away from the window in an anechoic chamber. Different configurations of the system components were investigated, and error sensor locations were found to be crucial to the control performance. Average broadband attenuation from the system can reach 13 dB from 100 Hz to 1000 Hz.

(a) (b) (c)

Figure 7: (a) Ground plan of the transmission test rooms. (b) A photo of one configuration of the adaptive noise-blocker for a tilted window. (c) A photo of the receiving room [23].

2.8 Spain

In Spain, Professor Romeu and his team from the Universitat Politècnica de Catalunya presented an experimental work on active control of sound transmission through a restricted opening bottom hinged window in 2014 [24]. A single-input single-output system was used to attenuate the sound transmission caused by aircraft pass-by through the aperture of the window when it is partially opened in the exposed façade of a dwelling located near an airport. They found that the use of the active cancellation was effective (about 3 dB) at the low frequency range (100 Hz and 125 Hz third octave bands), which can recover a significant portion of the loss of insulation effectiveness due to the presence of an aperture when the window is partially opened. Poor coherence between the error and reference signals at certain frequencies and the complex geometry of the aperture of the particular style of the hinged folding window limit the performance of the system. Figure 8 shows the location of the test window and room in the dwelling, schemes of the active window and the ANC system.



(a) (b) (c)

Figure 8: (a) Location of the test window and the room in the dwelling. (b) A Scheme of the active window. (c) A Scheme of the active noise control system [24].

3. Discussions

For research on active control of sound transmission through windows with nature ventilation, recent advances can be roughly divided into two categories. The first category is direct control of sound transmission through window openings, which installs secondary sources on the openings or on the edges of the openings to control sound prorogation through the openings. The AAS windows developed in Japan and Singapore, the Active Window configuration in France, and the research in Republic of Korea, Germany, and Spain belong to this category. The AAS windows locate the secondary sources on the path way of the opening windows and target for large windows, while other research installs the secondary sources on the edges or boundaries of the openings and targets for small size openings such as that of small windows or partially opened windows. The advantages of this category are simple installation and high air circulation rate; however, it has poor performance in the middle to high frequency range and the potential high cost.

The second category is the ANC plenum windows, which apply ANC on the plenum structures transformed from opening windows. The research in Hong Kong and China, and the Active Labyrinth configuration in France belong to this category. The ANC plenum windows integrate both passive and active noise control methods in the system, where the plenum chambers provide noise attenuation in the middle to high frequency range while at the same time provide certain degree of air flow for natural ventilation, and the ANC components attenuate low frequency components of noise that propagates through the plenum chambers. The plenum chambers transform the original three dimensional free space sound field problems into one dimensional duct acoustic problems or low order acoustic cavity problems so that ANC can be applied more efficiently with better noise reduction performance and lower cost. The disadvantages of this category are their complicated structure and some loss of the air exchange rate.

Up to now, there is still lack of a mature practical solution to the problem of good noise insulation windows with nature ventilation. Many issues need to be addressed to make successful commercial natural ventilation ANC window products. First, the size of the control sound sources needs to be reduced, and thin small powerful loudspeaker systems with reasonable good low frequency response are required. Second, the robustness and performance of the active control system need to be improved, so that the system can achieve good noise reduction under all circumstances such as that with strong wind, heavy rain and storms with thunders. Finally, the cost of the controller and the system needs to be reduced so that mass production markets and building industries can accept it. For both categories, short delay AD/DAs and a powerful DSP or FPGA are necessary because of the causality requirement. Special designed chips might be necessary to bring the cost down.

For the AAS systems in the first category, the challenge is that lots of channels are needed for a relatively large window, leading to less feasibility for practical applications. Future research directions can be focused on the development of compact decentralized multiple adaptive ANC controllers and the understanding of the mechanisms and physics of the systems with multiple direction incidence sound. Because secondary sources located in the middle of the opening are sometimes difficult to implement in some applications, applying secondary sources only at the edge of the openings seems more practical. It has been found that an upper limit frequency exists for effective global control when secondary sources are installed at the edge of an opening, so it might be necessary to have lattice form ANC windows, where a large window is divided into many small lattices with secondary sources being installed on the frames of these lattices. At present, the ANC plenum windows seem the most practical solution. Their performance has been validated and the several prototype systems have been demonstrated successfully. Although more tests are still needed to make them to be mature products, the real challenges are the marketing and the cost.

4. Conclusion

This paper introduces recent advances on active control of sound transmission through windows with nature ventilation in the last 5 years. ANC plenum windows, which can provide broadband noise control at reasonable cost, are the closest to applications. Applying ANC directly on windows or openings need further research and the lattice form of these kind windows might be a solution.

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