Active acoustic windows: Toward a quieter home

Lam Bhan and Gan Woon-Seng

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Environmental noise (also known as noise pollution) is a prevalent feature of any urban soundscape. Of the numerous environmental noise sources (e.g., aircrafts, road traffic, railways, industries, and construction), the World Health Organization (WHO) has identified road traffic noise as one of the main contributors to urban noise pollution.

Urban noise exposure has been linked to myriad health risks by an increasing number of health studies, as highlighted by Fritschi et al. Five major health effects were identified from the compilation of health studies: cardiovascular disease, cognitive impairment in children, sleep disturbance, tinnitus, and annoyance. Additionally, the observed health effects as a result of exposure to different noise levels (in decibels) was summarized by the WHO in Table 1.

Escalating vehicular usage in densely populated areas usually leads to congested road networks that may be in close proximity to current (and future) residential areas. The resulting inadvertent exposure to unhealthy noise levels has prompted governments around the world to explore noise control measures for safeguarding public health.

Coping with traffic noise

Passive noise barriers are a common sight in cities where residential areas are in close proximity to noisy transport infrastructures (e.g., highways, railway tracks, and airports). Erecting such barriers requires large amounts of space and incurs substantial costs, so it is not always a viable solution.

For a noise barrier to be effective, it has to be at least as thick as the wavelength of the noise source. According to Fig. 1, the spectra of traffic noise measurements show a general trend of higher energy in the lower frequency region (i.e., <4,000 Hz) with a peak at 1,000 Hz. Therefore, the lower end of the spectrum will hardly be attenuated by the noise barriers due to the thick barrier required. For example, according to the general wave relationship,

$$c_o = f\lambda,$$

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TABLE 1. The effects of various sound pressure levels (SPLs) on the health of the population from the WHO's report.

AVERAGE NIGHT NOISE LEVEL OVER A YEAR	HEALTH EFFECTS OBSERVED IN THE POPULATION
Up to 30 dB	No substantial biological effects are observed (subject to individual differences).
30–40 dB	Several effects on sleep observed but seem modest even in the worst cases. Vulnerable groups (e.g., children and the elderly) are more susceptible.
40–55 dB	Adverse health effects observed among the exposed population. Many people adapt their lives to cope with the noise at night. Vulnerable groups are more severely affected.
Above 55 dB	Considered increasingly dangerous for public health. Frequent occurrence of adverse health effects with a sizeable proportion of the population highly annoyed and sleep disturbed. There is evidence that the risk of cardiovascular disease increases.

where c_o is the speed of sound in air (~340 ms^{-1}); f is the frequency in Hertz; and λ is the wavelength in meters, a 0.34-m-thick noise barrier is required to attenuate frequencies only as low as 1,000 Hz. Additionally, noise signals (especially lower frequency) can propagate above the noise barriers and still affect units in the higher levels of high-rise buildings, as illustrated in Fig. 2.

At the individual level, one may try to reduce noise from propagating into his/her dwelling by simply shutting the windows. Although this is rather effective, with SPL reductions in the range of 24–45 dB, according to the WHO, it still does not attenuate low-frequency sounds effectively. Closed windows also translate into poor ventilation of the dwelling, which is essential for tropical regions and summers of temperate zones. A lack of ventilation may even directly cause sleep disturbances, as reported in a Swedish study highlighted by the WHO.

Even though PNC methods are effective at damping noise over a large frequency range, they are less effective at the lower frequencies due to the thickness of media required.

The aforementioned methods of sound insulation are known as passive noise control (PNC) methods, where physical media are used to "shield" a listener from noise sources. Even though PNC methods are effective at damping noise over a large frequency range, they are less effective at the lower frequencies due to the thickness of media required.

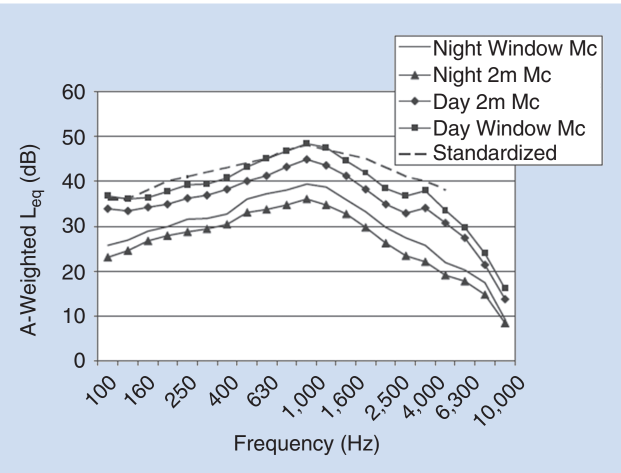

FIG1 Spectra averages from window microphone measurements by Jagiatinskis and Fiks.

Therefore, active noise control (ANC) methods may hold the key to a practical noise mitigation solution for protecting the health of an ever-increasing urban population. ANC methods have been shown to be more space- and cost-effective at attenuating low frequencies and are becoming increasingly realizable due to the recent development of efficient algorithms and powerful low-cost processors. Moreover, an ANC system retrofitted to open-windows may potentially attenuate low-frequency traffic noise while still allowing natural ventilation.

Development of ANC systems

ANC works on a simple but elegant principle of superposition depicted in Fig. 3. An "antinoise" acoustic signal is generated (by a control/secondary source) with the same amplitude but with opposite phase to cancel the undesired noise from the primary source [Fig. 3(a)].

Today, the field of ANC is well established, with numerous publications (Kuo and Morgan; Nelson and Elliott) detailing the acoustic principles and implementations of ANC systems. A classic example of an ANC system in a duct is illustrated in Fig. 4, where a secondary source speaker generates the antinoise signal to achieve cancelation at the error microphone location. The reference microphone is the detection sensor providing knowledge of the incoming wave, and the error microphone acts as a feedback mechanism to an adaptive algorithm for achieving optimum cancellation.

ANC can be generally classified by its control system types (feedforward or feedback) or by the number of channel (sensor or actuator) configurations (single- or multichannel). Figure 4 shows a single-channel feedforward system, where a reference signal is forwardly fed to the digital controller by a single sensor (i.e., one reference microphone) and an error signal is adaptively fed back to the controller also with a single sensor (i.e., one error microphone) to generate an antinoise signal with an individual actuator unit (i.e., one loudspeaker). In contrast, feedback systems omit the use of reference sensors and generate the antinoise based solely on feedback from the error sensor(s). A multichannel ANC system (either feedforward or feedback) with multiple microphones and secondary sources is usually used to widen the "quiet zone."

Modern ANC systems detect changes in the primary noise using electronic sensors (e.g., microphones and accelerometers) and analyze them with powerful digital signal processors (DSPs) to yield an accurate antinoise signal. The practical implementation of ANC systems has become more apparent today, owing to the development of faster DSP chips at increasingly affordable prices.

ANC's rise in prominence is attributed to its applications in everyday situations. ANC headphones are one of the most successful implementations of ANC, along with its use in air-conditioning ducts, motorcycle exhausts, and power transformers. More recent innovative applications of ANC, summarized by Kajikawa et al., include: a motorcycle helmet retrofitted with ANC to shield the rider from unhealthy levels of engine noise, a novel snore-noise cancellation system to reduce sleep disturbances caused by snoring, magnetic resonance imaging (MRI) ANC systems for reducing MRI noise exposure to hospital personnel, and an ANC system for reducing equipment noise in infant incubators.

These applications, known as *local ANC* (noise control in confined spaces), have demonstrated the effectiveness of ANC in enclosed regions (e.g., within the ear cup of the headphones).

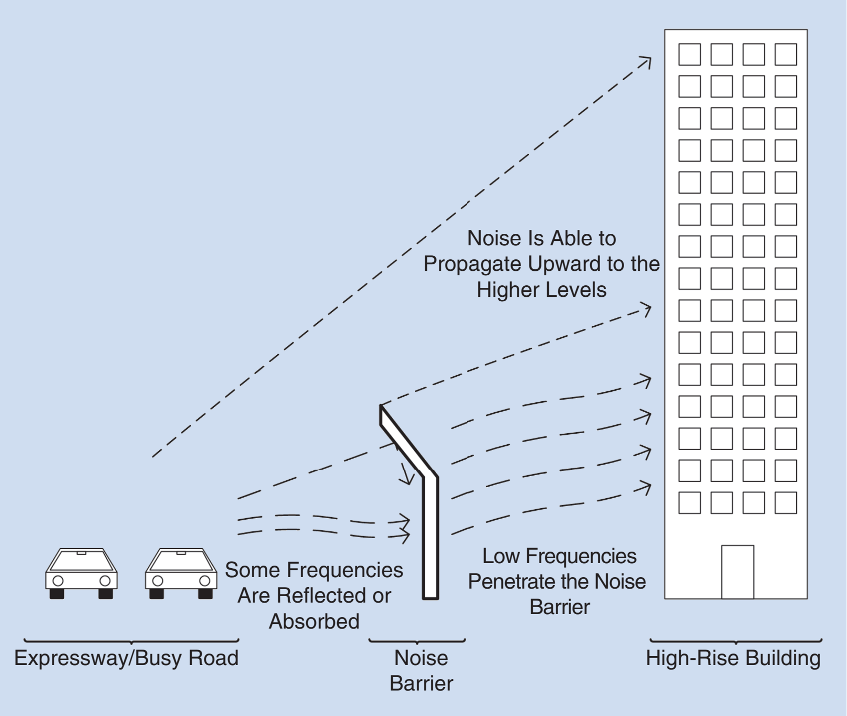

FIG2 Noise propagation in a typical noise barrier.

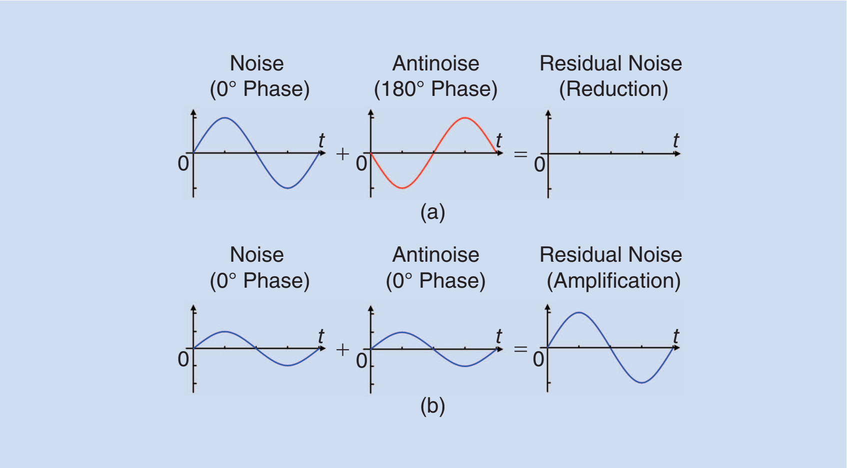

FIG3 Two extreme cases of superposition: (a) total cancelation by out-of-phase waves and (b) amplification by in-phase waves.

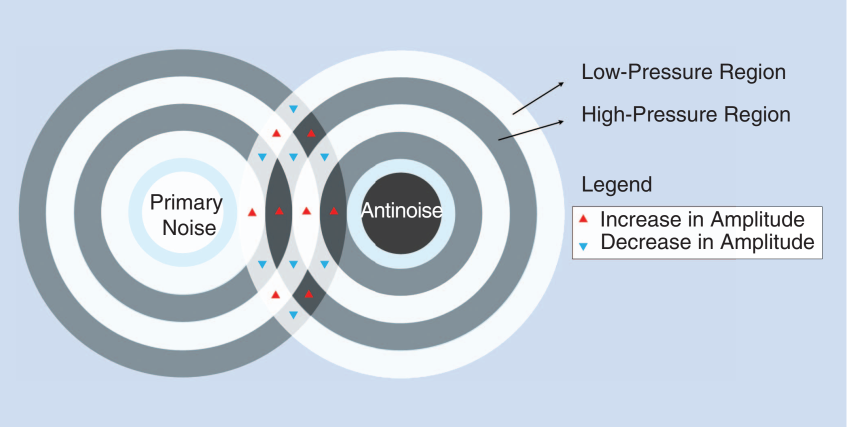

FIG4 Noncoherent sound fields from the primary and secondary sources.

Today, several research groups have illustrated that open-window ANC systems may be a potential solution to the noise (and ventilation) problem.

Conversely, actively controlling noise in a large three-dimensional space, also known as *global ANC*, is a complex problem that is an active area of research today.

Complexity of global ANC

Applying ANC to control traffic noise can be viewed as a global ANC application due to the large target area desired (e.g., an entire bedroom). The challenges of global ANC, highlighted by Kuo and Nelson, can be classified into

1) the coherence and the size of the control field
2) the causality problem
3) the placement of sensors and actuators.

Coherence and size of the control field

From the theory of superposition, illustrated in Fig. 3, total cancellation occurs if the sound field of the noise source is overlapped exactly with a sound field of the same amplitude but in opposite phase. Figure 4 shows the omnidirectional propagation of primary and secondary sound fields generated by single point sources, illustrating the effect of noncoherent sources. Ideally, the regions of high pressure (dark colored) will cancel regions of lower pressure (light colored) to create a large "quiet" zone if they overlap perfectly. The misalignment of the two sound fields in Fig. 4, produces zones where the sound is minimized (blue arrow) and zones where the amplitude is undesirably increased (red arrow). Since it may not be possible to setup a secondary source as large as the primary source (i.e., a loudspeaker the size of a typical window), Nelson and Elliott suggested and demonstrated the use of multiple secondary sources to generate a combined sound field of the required dimensions.

The causality problem

The use of electronic circuits inevitably introduces constraints to the setup of an ANC system. In essence, the total time taken for the electrical components to detect, analyze, compute, and finally transmit to the secondary source must be less than the time it takes for the wave to travel from the detection microphone to the secondary source (Fig. 5). This constraint is formally known as the *causality problem* and is represented mathematically by Nelson and Elliott as,

$$l \geq \tau c_o,,$$

where l is the separation (in m) between the detection sensor and the secondary source, τ is the total delay of the system components, and c_o is the speed of sound in air. Thus, the number of electrical components, the speed of the algorithm, and the response of the electrical sensors will ultimately determine the distance between the reference microphone and the secondary source.

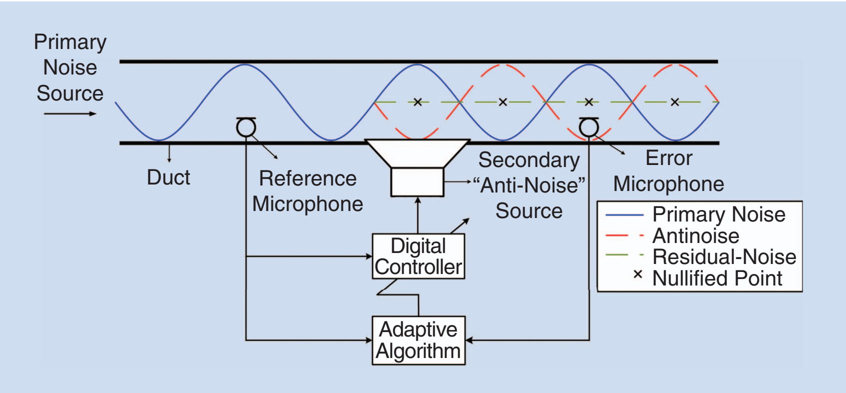

FIG5 An ANC setup in a duct.

Placement of sensors and actuators

The positioning and quantity of multiple sensors and actuators (secondary sources) have to meet the requirements of size (of the desired sound field) and work within the causality constraint. A larger number of sensors and/or actuators directly increases τ, due to the presence of more electrical components and longer computation time.

Additionally, according to Nelson and Elliott, the attenuation level (in dB) is directly proportional to the number of secondary sources and inversely proportional to the separation (in wavelength) between the primary and secondary sound fields.

Therefore, the traffic noise problem can be approached intuitively by taking the window opening as the origin of the primary noise, and actuators can be placed close to the primary source to achieve good attenuation. The window approach will be classified into two categories: 1) closed-window ANC systems and 2) open-window ANC systems.

Closed-window ANC

In studies compiled by the WHO, double-glazed windows (commonly found in temperate regions for thermal insulation) can reduce outside noise SPL by up to 45 dB. However, similar to noise barriers, double- or even triple-glazed windows perform poorly at attenuating low frequencies. To overcome the poor low-frequency attenuation properties of all windows in general, researchers such as Jakob and Möser and Hu et al., proposed closed-window ANC solutions targeted at low-frequency noises.

Jakob and Möser proposed both the multichannel feedforward and feedback ANC systems for double-glazed windows, illustrated in Fig. 6(a). The experimental setup of the feedback system consists of eight secondary sources and four error microphones built into the cavity between the glass panels. For the feedforward case, an additional reference microphone is placed outside the window. The feedforward technique, with an approximate reduction of 7 dB, was consistently more effective compared to the feedback technique with only 3.4–6 dB attenuation, for real traffic noise.

On the other hand, Hu et al. proposed a multichannel feedforward ANC method using a transparent thin-film actuator as the secondary source that spans the entire face of the window. The experimental setup, shown in Fig. 6(b), also includes a pair of reference microphones and a pair of error microphones. A 6-dB drop in SPL was achieved for real traffic noise. The minimal attenuation for both ANC methods (~6 dB) may be due to the passive attenuation by the physical windows. Moreover, closed-window ANC systems are not suitable for areas that require windows to be opened frequently for ventilation (e.g., tropical regions).

Open-window ANC

Windows that can abate traffic noise while still allowing to be opened frequently for ventilation have generated particular interest in the research community and environmental agencies of various governments. Today, several research groups have illustrated that open-window ANC systems may be a potential solution to the noise (and ventilation) problem. Currently, there are several prominent research groups proposing different open-window ANC solutions.

Sachau et al. emulated a bedroom scenario with a partially open window and a single bed, as shown in Fig. 7. A multichannel feedforward system with (1) reference microphones outside of the window, (2) two error microphones embedded in the pillow, (3) two secondary source loudspeakers embedded on the headboard, and electro-dynamic speakers placed outside the room to simulate the primary noise, was proposed. The sound field was measured with a (4) robotic rack

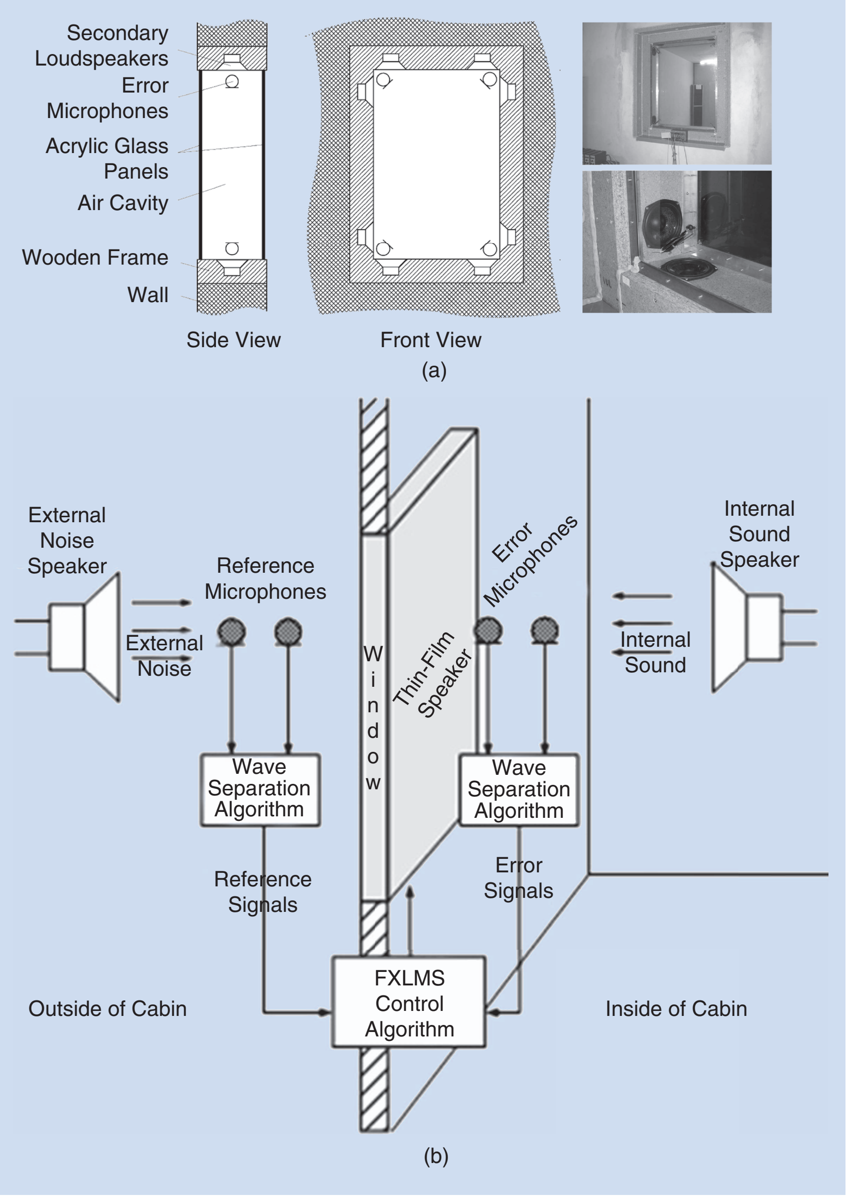

FIG6 (a) Jakob and Möser's schematic diagram and experimental setup. (b) A schematic diagram of the thin-film speaker setup by Hu et al.

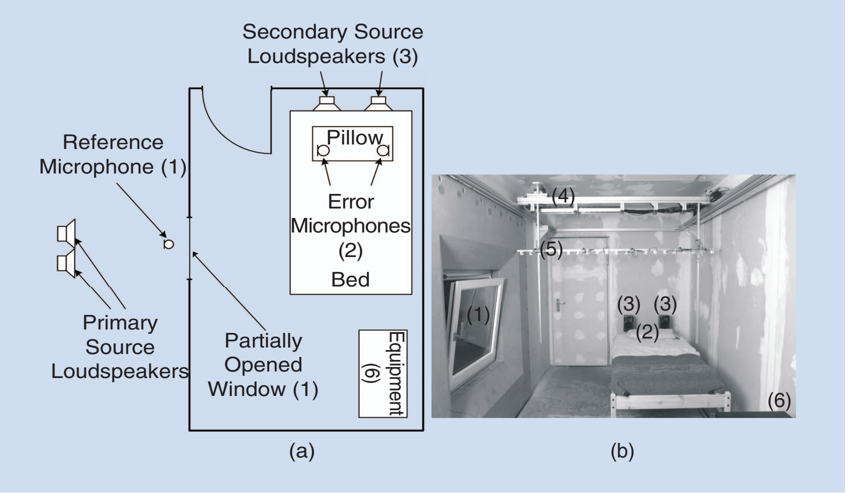

FIG7 (a) A schematic diagram and (b) an experimental setup of the ANC system by Sachau et al.

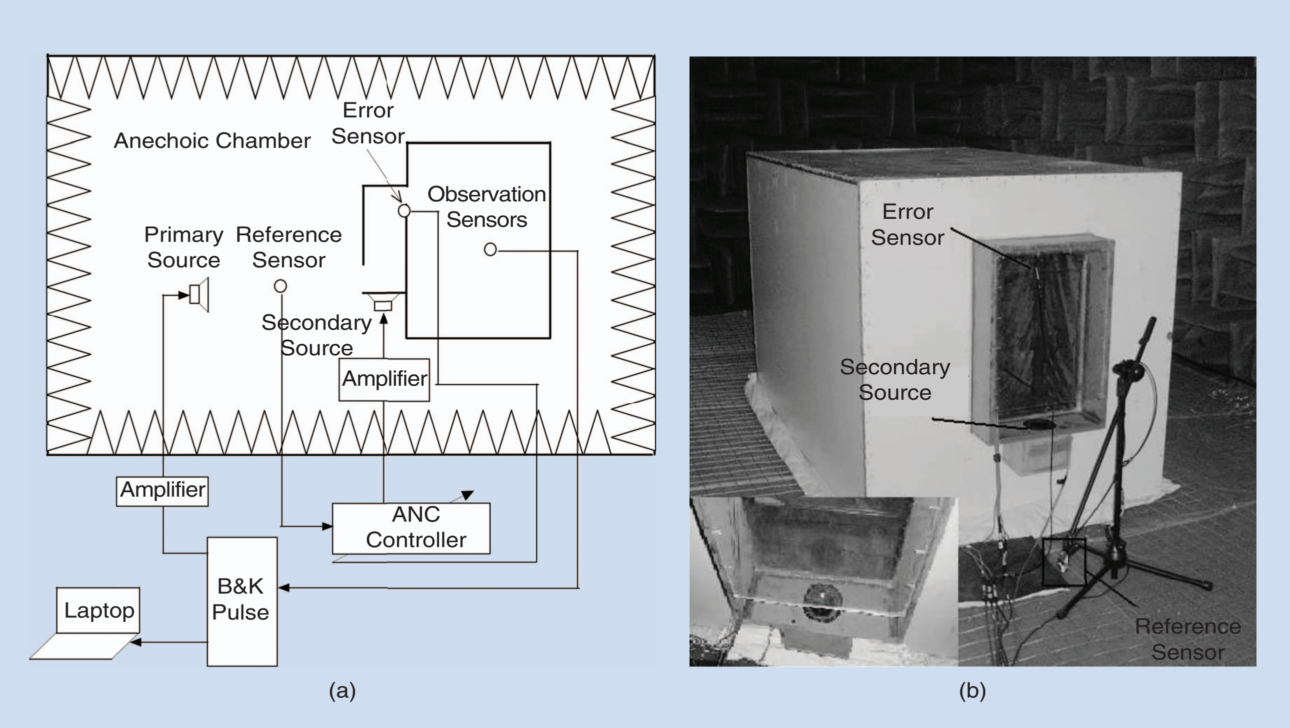

FIG8 (a) A schematic diagram of Huang et al.'s cascading window setup and (b) an experimental setup of the single-channel variant.

Modern ANC systems detect changes in the primary noise using electronic sensors (e.g., microphones and accelerometers) and analyze them with powerful digital signal processors (DSPs) to yield an accurate anti-noise signals.

mounted with (5) an array of 21 microphones and all of the electronic components are placed in a rack (6). For broadband noise (80–480 Hz), an SPL reduction of 5.9 dB was achieved.

Huang et al. further investigated ANC on a cascading window system (i.e., a double-glazed window with a small rectangular opening on each side of the glass panel, similar to the structure periscope, depicted in Fig. 8). Although airflow was restricted two to four times in such a configuration, a certain level of comfort was still achievable owing to optimal configurations. Experimental validations had shown a 10-dB reduction in the range of 400–800 Hz when a double channel feedforward ANC system was used (i.e., two reference sensors 1 m away from the dual secondary sources, two secondary sources within the gap of the glass panels, and two error microphones on the window opening of the room).

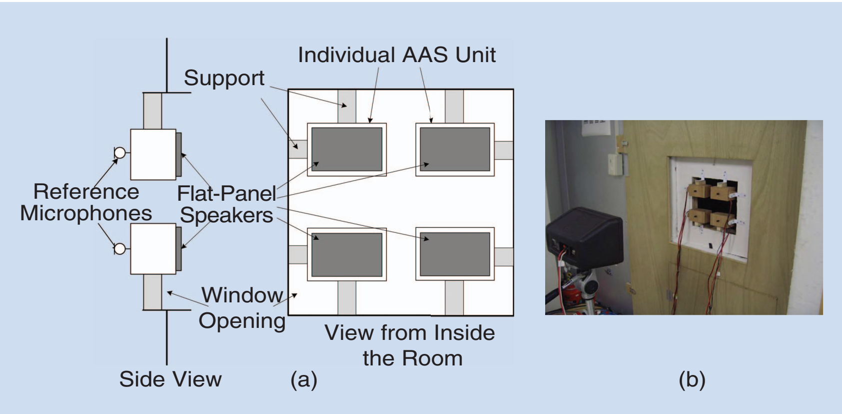

FIG9 (a) A schematic of the AAS window and (b) an experimental setup of the AAS concept by Murao and Nishimura.

Recently, Murao and Nishimura proposed an active acoustic shielding (AAS) concept that comprises four individual single-channel feedfoward ANC units integrated in a fully opened 250 × 250 mm window, shown in Fig. 9. Each AAS unit comprises a reference microphone directed at the noise source (outside the window) and a flat loudspeaker directed into the room to be controlled, which are separated by 50 mm of sound absorbent material. A pre-adapted system is deployed, where the controller's filter coefficients are adjusted offline and fixed using error microphones placed in the control field with the FXLMS algorithm. The final ANC setup eliminates the use of error microphones

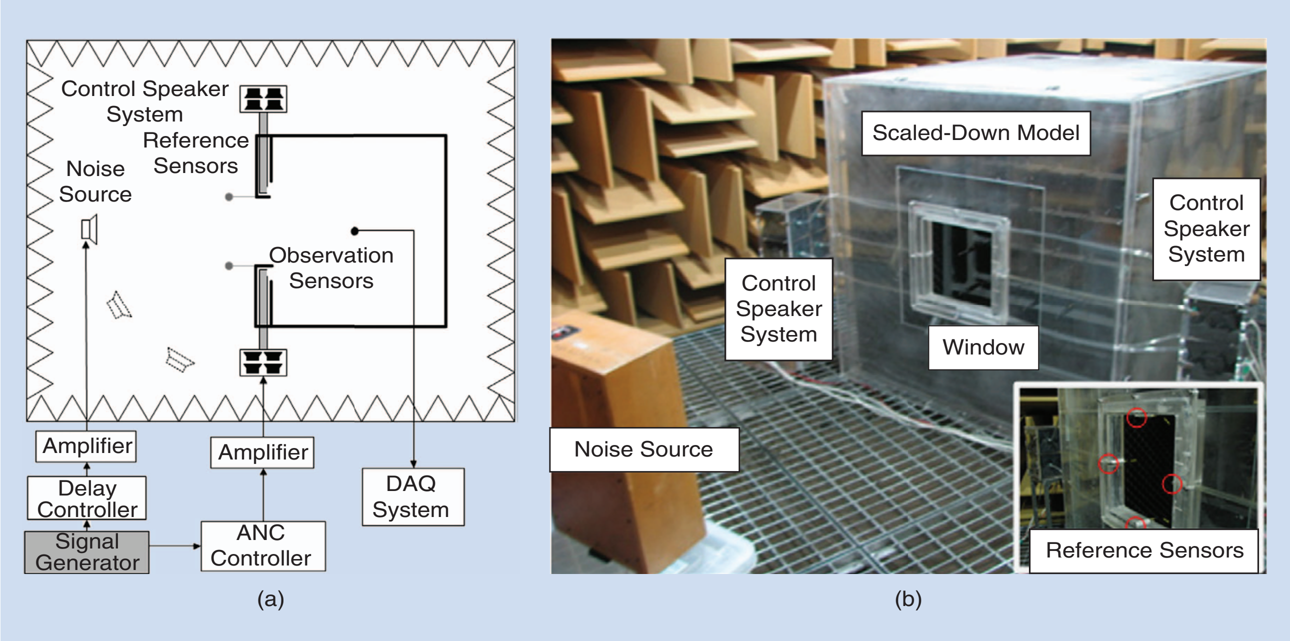

FIG10 (a) A schematic diagram and (b) an experimental setup of the ANC system by Kwon and Park.

and demonstrated a 10–15 dB reduction in bandlimited random noise (between 500 and 2,000 Hz) when the noise is normal (0° incidence) to the AAS unit. A similar reduction up to 1.5-kHz range was reported for oblique noise incidence (30°) only, a combination of both normal and oblique cases (two primary sources), and moving sources in the direction parallel to the setup at two speeds: 0.9 ms^{-1} and 1.8 ms^{-1}.

Another fully opened window concept, illustrated in Fig. 10, was recently proposed by Kwon and Park. The multichannel feedforward system comprises four reference microphones extended from the centre of the four sides of the window frame, eight control sources distributed evenly around the window frame directed into the room, and the primary noise source emitted by a loudspeaker 1.4-m away from the window. Similar to Murao and Nishimura's setup, Kwon and Park's also employed a pre-adapted technique. A "virtual-sensing" algorithm is introduced to estimate the reference noise signal so that causality can be achieved. Another novelty was the integration of an external loudspeaker system (often bulky) that places the control source at the desired location via sound-tubes. With the primary source excited at three incident angles (0°, 30°, and 60°), exterior noise was reportedly reduced by up to 10 dB in the frequency range of 400–1,000 Hz.

Although the effectiveness of traditional ANC techniques in the low-frequency regions is well suited for the reduction of road traffic noise, their inefficiency in the high-frequency range may pose a potential problem.

Limitations and the future of open-window ANC systems

The various open-window ANC methods have shown promise for the development of viable open-window ANC systems, which may eventually be installed in urban dwellings. Although some concepts are not off-the-shelf solutions, and have small openings (some even requiring major modifications to common window systems), they have been proven to be effective and may be adopted in the future development of acoustic window systems. For instance, Murao and Nishimura's combined individual single-channel ANC units can reduce a substantial amount of computational time needed in the adaptive algorithm; Kwon and Park's virtual sensing technique combined with a sound-tube system may solve certain physical constraints with regards to reference microphone placements and traditional loudspeaker systems respectively; and Huang et al. had displayed a truly adaptive ANC system in a cascading window structure that may be applied to partially opened windows.

However, ANC is not without its limitations. To achieve a large quiet zone, multiple antinoise sources and sensing microphones are required. As a result, implementation and maintenance costs will rise with every increment in the number of electrical components used.

Although the effectiveness of traditional ANC techniques in the low-frequency regions is well suited for the reduction of road traffic noise, their inefficiency in the high-frequency range may pose a potential problem. To cope with the residual high-frequency components, two techniques proposed by Kajikawa et al. could be used: 1) psychoacoustic ANC and 2) ANC with directional loudspeakers.

Psychoacoustic ANC techniques exploit the characteristics of human sound perception (psychoacoustics). Attenuation of low frequencies may cause the residual high-frequency components to be perceptually louder and considerably irritating. One method is to employ a masking technique to "cover" the irritable sounds, such as using soothing high-frequency sounds (e.g., a bird's singing and ocean waves).

The emerging field of parametric array loudspeakers (PAL) using ultrasonic emitters to generate audible frequencies has been proposed for directional ANC solutions. PAL ANC can be combined with conventional ANC to attenuate a broader range of frequencies, since PAL is effective in the higher frequency range (between 500–2,500 Hz).

To realize a practical and effective open-window ANC system, an innovative design approach that can overcome the constraints of causality and reduce noise in the entire room is needed. Furthermore, masking and PAL ANC techniques are areas that may be worthwhile to explore for their application in open-window ANC systems.

Read more about it

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About the authors

Lam Bhan (blam002@e.ntu.edu.sg) is currently pursuing his Ph.D. degree in electrical and electronic engineering at Nanyang Technological University.

Gan Woon-Seng (ewsgan@ntu.edu.sg) is an associate professor in the School of Electrical and Electronic Engineering at Nanyang Technological University. He is a Senior Member of the IEEE.

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