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Ten questions concerning active noise control in the built environment

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A B S T R A C T

Urban noise pollution is an omnipresent but often neglected threat to public health that must be addressed urgently. Passive noise control measures, which are less effective at reducing low-frequency noise and are often bulky and may impede airflow. As evidenced in automobiles, active control of cabin noise has resulted in lighter cars due to reduced passive insulation. Despite its long history and recent popularisation by consumer headphones, the implementation of active noise control in the built environment is still rare. To date, active noise control (ANC) has been demonstrated, at source, in construction machines and, in the transmission path, in noise barriers. Recent demand for naturally-ventilated buildings has also spurred the development of active control solutions at the receiving end, such as on windows. The ten questions aim to demystify the principles of ANC and highlight areas in which environmental noise can be actively mitigated. Since the implementation of active control in the built environment usually involves multiple stakeholders, operational concerns are addressed. To conclude, research gaps are identified that would enable increased adoption of ANC in the built environment. There is also renewed interest in applying intelligent ANC to tackle environmentally complex applications, such as varying noise levels in the earcup of ANC headphones, particularly with the advent of the low-cost, low-power, highly-efficient embedded electronics; advancing speaker technology; and new impetus from digital signal processing and artificial intelligence Algorithms.

1. Introduction

Urban noise exposure is an underestimated threat to public health. The World Health Organization (WHO) has highlighted the growing body of evidence linking noise pollution to a myriad of health risks in the recently updated: "Environmental Noise Guidelines for the European Region" [1,2]. Noise exposure is not limited to the European region, the WHO guidelines are general recommendations for all countries as the underlying evidence has been gathered from around the world. This has also prompted some to label environmental noise as the "new second-hand smoke" [3].

1.1. Noise control in the built environment

To combat noise pollution, mitigation measures can be applied at the noise source, along the noise propagation path, or at the receivers' end. These measures are stated in the order of their effectiveness, since noise control at the source is the most effective, and it is generally less efficient to control noise at the receiver. For environmental noise (e.g. transportation noise, construction noise, aircraft noise), control at source is usually a difficult problem as many stakeholders are involved, e.g. vehicle manufacturers, government bodies, transport operators, and individuals. Measures along the propagation path, such as noise barriers, can be effective for high-rise, land scarce cities. Recently, the noise problem is further compounded by the demand for naturally ventilated buildings whereby façade openings act as point of entries for noise.

Traditional approaches gravitate towards passive methods, whereby physical structures are employed to disrupt the sound waves before it enters the building interior, e.g. noise barriers, façade shielding. These passive methods have the advantage of simplicity and do not require power, but generally restrict the airflow and are not effective in the low-frequency range (i.e. less than 1000 Hz). Theoretically, these shortcomings can be overcome by active mitigation methods, also known as active noise control (ANC). The ANC methods generally require a sensor to detect the impinging noise, a controller to calculate the out of phase 'anti-noise' wave, and an actuator to produce the anti-noise, which

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minimizes the noise at a feedback sensor. The anti-noise wave is a copy of the actual noise but with an inverted phase, which destructively interferes with the impinging noise thereby neutralising it. Despite its roots in the mitigation of noise from large transformers [4], successful commercial implementation of ANC has thus far been limited to small or enclosed zones (e.g. headphones, aircraft and automobile interiors). Adoption of ANC in the built environment is hampered by the lack of understanding behind the principles of active control and its physical limitations.

1.2. History of active noise control and its applications

Fig. 1 shows the evolution of the ANC technology. The development of active noise control started with Paul Leug's patent in 1936 [5], where he described the principle of active noise control in a physically realistic way. However, there was no real-world application at that time. Subsequently, there were several experiments carried out by Olson on electronic sound absorption using analog technology, but due to its limitation and size, there was no technical application. Later, Conover, an engineer from General Electric, filed a patent on noise reduction system for a transformer. However, his efforts were hampered by a lack of theoretical knowledge and availability of any fast digital processor that can adjust their systems in a closed loop fashion.

Since noise sources and acoustic environments are generally time varying, the controller must be adaptive and response to the time-varying frequency content, amplitude, and phase of the noise source. It is the classical work on adaptive signal processing by Widrow and Stearns in 1985 [6] that laid the foundation of filtered-input least--mean-square adaptive algorithm for active noise control. This algorithm can be implemented digitally in digital signal processor (DSP), which was introduced in 1980s, with fast digital computational hardware that computes the anti-noise signal with precise control of amplitude and phase.

These two important advancements in algorithm and digital processors spurred the growth of ANC in various real-time demonstrations and products in noise control for air ducts [7,8], noise reduction in headphones [9], automobiles [10], and aircrafts [11] in the 80s and 90s, as shown in Fig. 1. Several classic ANC textbooks based on the acoustics perspective of ANC [12]; and those focused on signal processing [13, 14], provide the theoretical framework to build new practical ANC applications. In the past decade, there has also been a significant increase in ANC-related patent activity, which indicates an increasing commercial interest and innovation in ANC applications. Based on a google patents search for unique utility patent families with ANC-related Cooperative Patent Classification (CPC) codes (i.e. A61F2011/145, G10K11/178, G10K2210, G10K11/178, H04R2460/01, F16L55/0333, F01N1/065), there are currently 2927 and 4702 patents granted and filed till 2020, respectively. A total of 1989 patents were granted since 2011, which is more than double the 938 patents granted from 1919 to 2010, as shown in Fig. 2.

To date, there are three main ANC applications and development tracks (as also indicated in Fig. 1), namely:

(i) ANC in headphones/"hearables", which has achieved the greatest success and popularity in integrating ANC into an ever-growing list of consumer hearables, ranging from low-cost earbuds to the high-end headphones.
(ii) ANC in automobile and aircraft cabins, which has evolved from cancelling dominating engine noise and blade passing frequencies for the comfort of driver and passengers to the rolling noise caused by tires against the road surfaces in electric vehicles.
(iii) ANC in open space is the toughest problem among all these three tracks. The main objective of this ANC track is to arrive at a global noise control in a large area, whilst minimising "spillover" to other areas.

To further elaborate, there are several successful examples of acoustic ANC applications in air, which include:

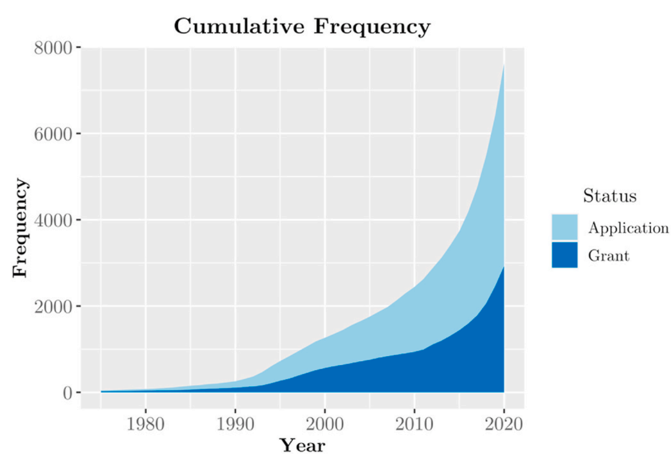


Fig. 2. Cumulative count of ANC-related patent families granted and filed (mutually exclusive) in each year till 2020, based on a search in the google patents database.

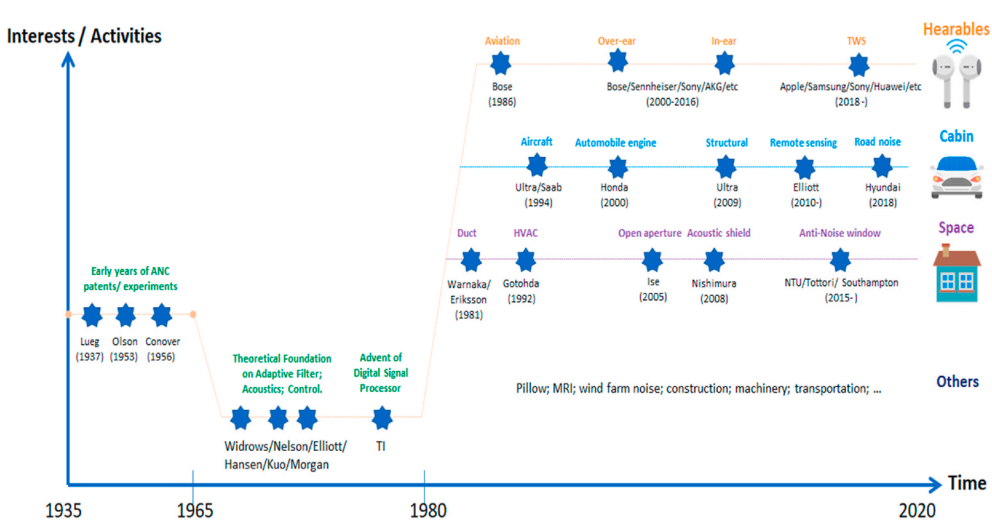


Fig. 1. The evolution of ANC technology and the continuous growth of its applications in consumer, vehicular and in the built environments. The three time periods, starting from its conception in 1936, through a period of dormancy from 60's till late 70's, to the current growth in ANC technologies due to the availability of high performance and low-cost processors and running the latest digital adaptive signal processing Algorithms. From the 80s onward, three main application and development tracks for ANC have taken place: hearables; cabin; and space.

(1) Duct noise reduction was the first application of ANC. Chaplin [8] and Ross [7] built real ANC silencers for marine engine exhaust noise and gas turbine exhaust noise respectively in early 1980s. Since then, many ANC systems has been applied for noise reducing of plant fans, air conditioner duct and engine exhaust duct [15]. Duct noise reduction is one of the easy, convenient, and useful applications of ANC.
(2) Interior noise reduction in propeller-driven aircraft [11] that has noise generated by the external propeller's rotation. Other interior noise ANC application for interior noise reduction includes the engine [10,16] and road noise [17–19] reduction inside the passenger car. Noise cancelling speakers can be placed near the headrest of a chair to cancel unwanted low-frequency noise at the ears of a person sitting in a chair. Alternatively, if speakers are not available near the person ears, they can be integrated with the audio playback system in the car. In yet another interior noise reduction application on noise in a cabin of a construction machine has also been reduced by using ANC technique [20].
(3) Headphones noise reduction is the most commercially successful ANC application. The spatial region to control noise is between the headphones and the eardrum, and this region is small as compared to the wavelength over the frequency range of interest. This application allows the passive earcup or earbud to attenuate high-frequency noises, and the ANC system cancel out low-frequency noises. ANC functionality is a must have in today's commercial headphones. Active noise control is used in personal hearing protector in military, mining, factory, and magnetic resonance imaging scanners.
(4) Free-space noise control through noise barrier that is installed with ANC based cancelling speakers on top of the barrier. This acoustic barrier consists of loudspeaker array placed on top of physical barrier and error microphones near the control point inside the barrier. This is controlled by not only analog feedback system but also fast digital feed forward collocated system with reference microphone. This acoustic barrier [21–23] can reduce noise propagates from any direction of moving noise sources, such as traffic noise. This technique is based on decentralized distributed ANC system applied to sound field boundaries [24].

In the built environment, where we are mainly dealing with free-space noise from machinery equipment and traffic noise from vehicles, including aircraft. There are several well documented ANC methods to reduce power transformer noise by placing loudspeaker array around the site [25–27]. A noise screen for mitigating noise from airports has also been proposed in Ref. [28], which generates destructive interfering plane wave to counter the impinging aircraft noise.

Sound shielding by a grid of distributed anti-noise sources has also been proposed in Refs. [29–32]. These anti-noise elements can be built into window frame or across the grille of the window to generate anti-noise plane wave to counter the environmental noise propagating into residential buildings. This structure allows for natural ventilation through the opened window, and at the same time, provides low frequency noise control and supplements conventional passive attenuation at high frequencies. Potential drawbacks in applying ANC in built environment is the requirement of additional energy to power the ANC system and the ease of maintenance. However, an ANC system generally consumes power only when required and sustainable energy sources could be employed. The increasing durability of actuators and sensors will also enable the ANC system to withstand the harsh in-situ conditions.

To reiterate, this paper focuses on the active control of noise propagating through the air in the built environment. However, it is worth noting that there are other relevant forms of active control, such as active structural acoustic control (ASAC) [33,34] and semi-active control techniques [35,36], as well as associated techniques such as frequency response shaping for passive and active control [37]. Promising implementations of ASAC have been demonstrated in the active control of aircraft interior noise [38] and more recently in active device casings for industrial and home appliances [39,40], which can potentially control the noise at the source.

2. Ten questions (and answers) concerning active noise control in the built environment

2.1. What is active noise control?

Answer: Active noise control is the generation of an anti-noise using secondary source(s), which destructively interferes with the primary noise source(s) in air. The position of the secondary source(s) with reference to the primary noise is critical in determining the amount of noise reduction. Active noise control can be performed in three spatial regions: (i) at or near the primary noise source, which is the most effective approach (such as at the machinery and exhaust source). (ii) It can be applied to propagating noise by building a noise barrier with secondary sources placed on top the barrier. (iii) Lastly, it can also be applied at the receiving end of the user (such as ANC headphones). Therefore, there are generally two noise control approaches (namely, local and global) in controlling the noise source.

Local control of sound around human ears is possible, forming a "quiet zone" of noise reduction around the cancellation point near the opening of the ear canal, especially at low frequencies. Since the diameter of a quiet zone (i.e. 10 dB reduction) is approximately a tenth of the acoustic wavelength, λ, it is physically limited at higher frequencies. Local active control of sound is particularly suited for applications, like headphones and headrests, where sound control is targeted around the ears. Recent work on applying head tracking for ANC in automobile [41] has also shown the feasibility of a dynamic local noise control, whereby the quiet zone follows a user's head movements in an automobile.

Global noise control refers to the control of the primary noise source by using one or more secondary sources (or loudspeakers) to reduce the total acoustic power output. For global noise control in free space, the distance d between the primary noise source and the secondary sources determines the amount of noise reduction, given a fixed number of secondary sources. Typically, to achieve 10 dB attenuation in total noise power, a separation of normalized distance (d/λ) of up to 0.1 for a single secondary source [14] is allowed, where λ is the acoustic wavelength.

A general block diagram of ANC requires a control filter that takes in a reference signal from a reference sensor such as a microphone and the output of the control filter is then fed to a secondary source (such as a loudspeaker) to produce the anti-noise, as shown in Fig. 3. Observation microphones (commonly known as error microphones), which are positioned near the control region, are used to detect the amount of noise control at its location. The error signal is fed back into the control filter to adjust the control filter's coefficients until the anti-noise matches the noise signal spatially and temporally at the error microphone position.

Fig. 4 shows the tonal noise reduction contours for a range of amplitude and phase errors between the primary and secondary sound fields. An active noise control filter that results in an anti-noise that perfectly matches the noise in both amplitude and phase (shown as the origin in Fig. 3) can completely attenuate the noise. However, a mere ±0.9 dB amplitude offset and ± 6-degree phase offset of anti-noise from the actual noise results only in 20 dB noise reduction, which is still a significant reduction, corresponding to a quartering in the subjective level of the sound or perceived loudness. Therefore, in practice, it is very difficult to have this amount of noise reduction, especially at higher frequencies, for example since the phase error associated with a time lag increases with increasing frequency and harder to compensate for. Depending on the type of ANC applications, there is a consensus that achieving at least a noise reduction of 10 dB (to 20 dB) is significant

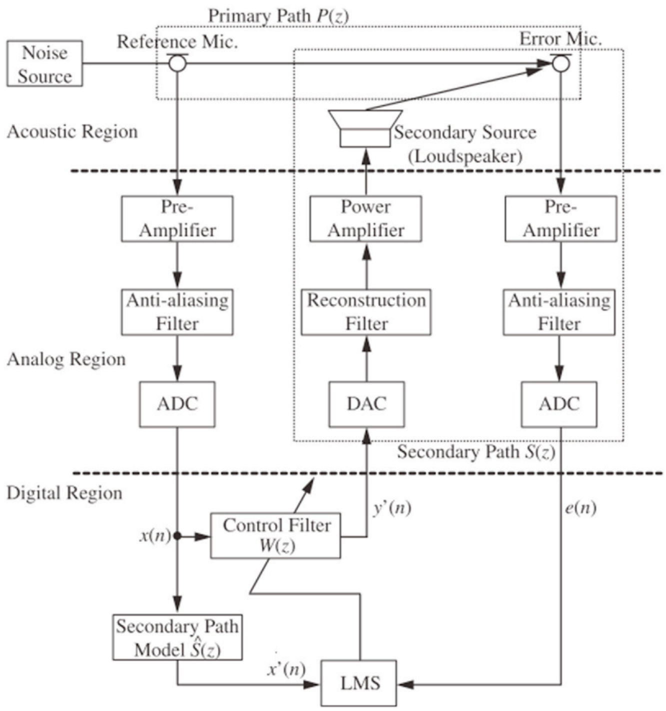


Fig. 3. Shows the building blocks of a single-channel active noise control system. It consists of three main regions of acoustic; analog; and digital. In the analog region, Analog-to-Digital (ADC) and Digital-to-Analog (DAC) are used to convert the analog signal received from sensors to digital sample for processing and vice versa, respectively. The least-mean-square (LMS) algorithm is used to adjust the weights in the control filter to adapt to the anti-noise to match to the noise amplitude and opposite phase.

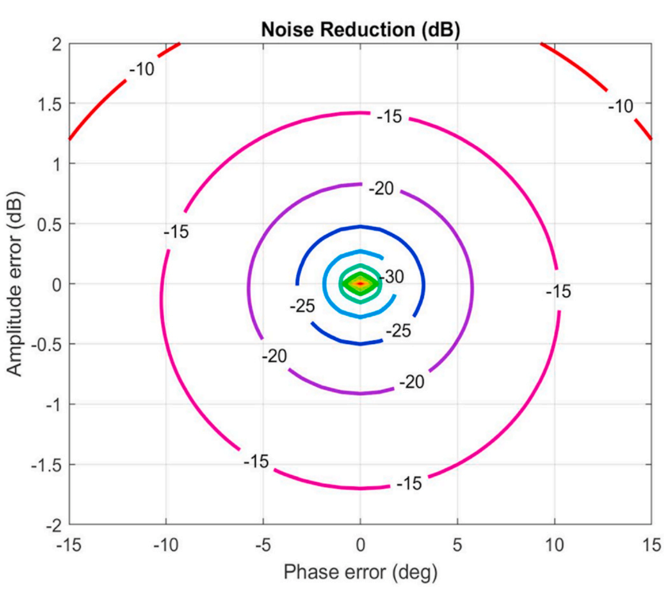


Fig. 4. A noise reduction contour governs by the equation: For a single noise frequency reduction, where phi and delA denotes the phase error and amplitude error, respectively. Note that the term error refers to the mismatch (spatial and temporal) between the noise frequency and the anti-noise frequency.

enough for user to experience at least a halving of perceived loudness.

Analog vs Digital Processing: As shown in Fig. 3, digital processing is being used to adaptively generate the anti-noise. Digital processing requires the sensed analog noise signal to be digitized before processing and afterward, generating an analog version of the anti-noise that destructively interferes with the disturbance. Therefore, designing a digital ANC system requires careful selection of low-latency electro-acoustic components with fast domain conversion and processor that can handle high sampling frequency (usually over-sampling with respect to the noise bandwidth to achieve micro-second sampling). The key advantages afforded by digital processing through analog-digital-analog domain conversion, includes its adaptability to changing noise, flexibility in configuring multi-channel adaptive noise control through programming, and the ability to integrate ANC with new functionalities (e.g. automatic gain control, equalization, active profiling) into a single system-on-a-chip. Furthermore, with high-resolution analog-to-digital converter (ADC) and digital-to-analog converter (DAC), the digital system can achieve higher signal to noise ratio (SNR) output than an analog system, which undoubtedly betters its noise reduction performance. In contrast, an analog active noise control [42] trade-offs the digital advantages with extremely low latency that results in good causality performance [42,43]. With recent advancements in digital and domain conversion technologies [44,45], however digital ANC is becoming the de facto processing platform for today's ANC applications.

Centralized vs Decentralized control architectures: In some applications, multiple-input and multiple-output active control is used to increase the zone of noise control. A centralized control architecture consists of a single controller that takes in all the error sensor information at different locations to generate the anti-noise to all the secondary sources. In this setting, global knowledge of the entire control zone is available. In contrast, the decentralized control architecture consists of multiple local controllers, and each controller handles its local error signal and actuator. There is generally no or little communication from one controller with its neighbours. Depending on the needs of different applications, centralized controller imposes a heavy computational complexity, cost of handling multiple sensors and actuators, and usually results in a more uniform and better performance compared to the decentralized controller. The latter approach is a much more scalable, and cheaper, but has an inherent risk of system instability.

Fixed-coefficient controller vs adaptive controller: The fixed-coefficient controller is becoming the de facto approach in commercial digital ANC headphones. Usually, the set of fixed-coefficients is obtained from careful tuning of the typical noise scenarios, which works satisfactorily for similar in-situ conditions. Different fixed-coefficient sets, which can be selected for different use cases [46,47], can be an attractive approach to obtain an instantaneous response to different noisy environments. In contrast, the adaptive controller, and error sensing is required to feedback and adapt the coefficients of the controller. This is illustrated in the Digital Region (bottom layer) of Fig. 3, where the control filter coefficients are continuously updated based on the strength of the error signal. A hybrid approach of fixed-coefficient-and-adaptive controller may prevent over-adjustment of the coefficients, leading to instability, and also results in a quicker noise reduction response.

2.2. What are the differences between active and passive noise control?

Answer: Passive control typically involves the use of damping or mass to reduce noise, whereas active control uses secondary sources to generate a noise field that destructively interferes with that from the original source. Active and passive noise control can be viewed as complementary techniques in terms of their effective frequency attenuation range, whereby active control mitigates low frequencies more efficiently and passive control performs better at high frequencies.

Traditional passive approaches have been the de facto noise control strategy, from control at source to control at the receiver [2]. Some examples include silencers on exhaust pipes of internal combustion engines (source), noise barriers along highways (propagation path), and multi-glazed windows (receiver). Passive materials achieve control either through absorption, diffusion or reflection of sound, which are not mutually exclusive. Since the density or thickness of the material is proportional to the acoustic wavelength, passive control is more cost-effective for shorter wavelengths of sound (i.e. high frequencies). The direct and indirect costs associated with the increased bulk is dependent on the context. For instance, stronger foundations for taller or denser noise barriers may drive up construction costs. On the other hand, additional weight due to damping in vehicles and aircraft decreases the fuel efficiency. Passive noise insulation approaches for exhaust and engine related noises must also be balanced with airflow and heat management for optimal operation. Nevertheless, passive approaches have been relatively scalable and effective to a large extent.

In contrast, successful mass adoption of active noise control has thus far been limited to confined spaces such as in automobile [10,19] and aircraft cabin interiors [11], and in headphones [9], as described in Section 1.2. However, the proven effectiveness of ANC at mitigating low-frequency noise is arguably more physically "compact" than their passive counterparts. This is evidenced in automobiles wherein bulky insulation has been replaced by ANC with the added benefit of improved fuel efficiency [18]. One of the main disadvantages of ANC is its need for electrical power. Hence, there is some resistance to the implementation of ANC in areas that, do not normally need power, e.g. noise barriers, windows. Examples of hybrid approaches, which involves augmenting the passive performance with active control, have been demonstrated on noise barriers, wherein ANC has been applied to extend the effective height of the barrier by minimising the diffracted waves over the top of the barrier [22,23,48].

Perhaps one of the greatest advantages of an active approach over a passive one in the built environment is its minimal impact to airflow [49,50]. Active control was first realized on air ducts [12,13,51] and more recently demonstrated on open windows [29,52–55], both of which were designed to minimise obstruction to airflow. For buildings, unobstructed airflow is important for natural ventilation (NV), an essential building design requirement to safeguard public health and to meet the United Nations (UN) Sustainable Development Goals (SDGs) [56]. Within buildings, NV is recommended by the WHO to improve indoor air quality [57], especially to reduce the risk of airborne communicable disease transmission, i.e. SARS-CoV-2/COVID-19 (severe acute respiratory syndrome coronavirus-2/coronavirus disease 2019) [58]. Globally, buildings account for about 40% of the total energy consumption and greenhouse gas emissions [59–61], with heating and cooling of buildings consuming majority of the total energy. Natural ventilation is known to reduce building energy costs by up to 50% [57,62–64], thereby contributing significantly towards goals 7 and 11 of the UN SDGs. The energy savings afforded by NV would be undoubtedly higher when taking into account the escalating cooling-energy costs due to the urban heat island effect, especially in high-rise urban areas [65–67]. Hence, ANC is a potential solution to the dilemma of noise ingress resulting from the resurging adoption of natural ventilation.

Notwithstanding the potential of ANC in controlling environmental noise, considerable care must be taken when designing an active control system [14,51]. Without fully characterising the physical environment in which the ANC system would be deployed, there is a risk of "spill-over", wherein noise is increased in areas outside the desired "quiet zone" [51]. For convenience, the abovementioned pros and cons of passive and active noise control in the built environment are summarised in Table 1.

2.3. How can we implement active noise control in the built environment?

Answer: Implementation of active noise control can be achieved across the entire transmission path, from the source, such as for construction machines, to the noise path, on top of noise barriers, and in open windows for example.

Although the most efficient way to control noise is at the source, implementation is usually prohibited by the complexity of the built environment, land scarcity, and the nature of the noise sources (e.g. moving vehicles). It is thus important to adopt a multi-pronged approach to simultaneously mitigate noise at the source, along the propagation path, at the receivers' end [2,68]. Commercially mature ANC products are currently still restricted to small enclosed personal spaces (e.g. aircraft interior, automobile interior, headphones) and are not widely deployed in the built environment. However, there are recent demonstrations of commercial ANC products by Japanese construction firms to reduce noise emitted by construction machines. To assess the current state-of-the-art and roadmap of ANC applications in the built environment, the technology readiness levels (TRLs) [69] of these applications can be estimated based on a 9-point scale, as shown in Table 2. Originally developed by the National Aeronautics and Space Administration (NASA), the TRL scale is widely adopted to assess the risk of technological investments, wherein a TRL of 1 indicates the lowest level of readiness and TRL 9 is matured development that is operationally proven. A TRL of 7 usually signals that the system is of sufficiently low

Table 1
Summary of pros and cons of passive and active noise control in the context of the built environment.

	Passive Noise Control	Active Noise Control
Pros	• Can be tailored for harsh environments • Effective at high frequencies • Easy to mass-manufacture/scalable • Does not require electrical power	• Effective at low frequencies • More compact • Minimal impact to airflow • Some degree of flexibility in selecting specific sounds to attenuate
Cons	• Some degree of maintenance required • Bulk/Weight-related cost ∝ Wavelength • Airflow/Heat management (Exhaust/Engine) • Cost ∝ Length and Height (Barrier) • Affects landscape aesthetics • Restricts airflow (façade element) • Unable to selectively dampen unwanted sounds and allow wanted sounds through	• Application-specific design • Mass producibility dependent on demand for application • Requires an electrical power source • Higher upfront R&D costs • Risk of noise spillover

Table 2
Standard technology readiness levels (TRL) scales adopted by NASA [69] and the HORIZON 2020 European Union program [71].

TRL	NASA definition	European Union definition
1	Basic principles observed and reported	Basic principles observed
2	Technology concept and/or application formulated	Technology concept formulated
3	Analytical and experimental critical function and/or characteristic proof of concept	Experimental proof of concept
4	Component and/or breadboard validation in laboratory environment	Technology validated in lab
5	Component and/or breadboard validation in relevant environment	Technology validated in relevant environment (industrially relevant environment in the case of key enabling technologies)
6	System/subsystem model or prototype demonstration in a relevant environment (ground or space)	Technology demonstrated in relevant environment (industrially relevant environment in the case of key enabling technologies)
7	System prototype demonstration in a space environment	System prototype demonstration in operational environment
8	Actual system completed and 'flight qualified' through test and demonstration (ground or space)	System complete and qualified
9	Actual system 'flight proven' through successful mission operations	Actual system proven in operational environment (competitive manufacturing in the case of key enabling technologies; or in space)

risk for productization or commercialisation [70].

Active noise control at source: There are currently two prominent applications of ANC for urban noise at source, namely mitigation of noise from construction equipment (e.g. excavators, genset) and the electrical hum at power transformer stations. It is worth noting that there are several demonstrations of ANC for construction machines by Japanese construction firms (TRL>7), as shown in Table 3. Based on the reports, active control appears to be targeted at the exhaust outlets of construction machines and gensets, as depicted in Fig. 5(a and b) and (c), respectively. Substantial reduction of more than 20 dB has been observed at the dominant low-frequency peaks near the machines, and more than 10 dB of reduction has been reported at the desired areas a distance away.

Although in-situ efficacy of ANC was first demonstrated for transformer noise, reports of transformer noise reduction with ANC are still confined to relatively few operational installations. At present, there has yet to be wide scale commercial implementations for the active control of transformer noise (TRL<8). From the examples in literature, it becomes apparent that the active control strategy is highly customised and greatly dependent on the physical environment. Active control strategies would differ for transformer stations in the open [25] or housed in a semi- [26] or fully-enclosed space [75], as shown in Fig. 6(a–c), respectively. Substantial noise reduction has been reported at the dominant electrical hum frequencies (e.g. 100 Hz, 200 Hz).

Active noise control along the propagation path: Erection of noise barriers is the foremost prevalent noise mitigation measure along the noise propagation path for traffic noise and railway noise [2]. Noise barriers are highly available solutions for moving noise sources, where control at source is usually not feasible nor practically enforceable. Although generally effective at mitigating noise its shadow region by about 3–7 dB [76,77], noise barriers are less cost effective for urban areas, especially around high-rise buildings. The effectiveness of noise barriers is contingent on their height, length, continuity, proximity to noise source, and upkeep [76]. Hence, land-scarce, high-rise urban cities are particularly challenging for the effective deployment of noise barriers. For instance, noise barriers must be exceptionally high to provide sufficient shielding to high-rise buildings, thereby requiring additional foundation. Moreover, the complex urban architecture and greenery poses another set of challenges to the continuity of noise barriers.

Active solutions have been proposed to minimise the diffracted noise over the top of the noise barrier or within the slits for improved reduction in the shadow region. This reduction of diffracted noise is equivalent to a virtual increase in effective height of the noise barrier [27]. Such active noise barriers (ANB) have been operationally demonstrated for traffic noise [23] and even commercialized for deployment at construction sites [48] (TRL>7), as shown in Fig. 7.

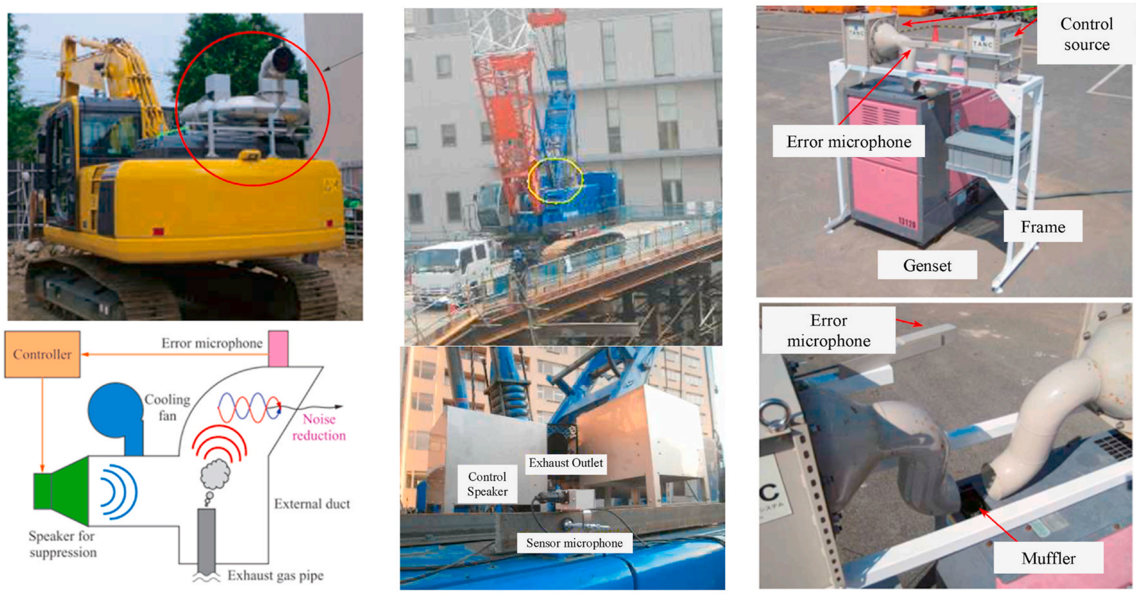
Notably, the active soft edge ANB system was installed in 2005 along two sections of route 43 highway in Japan, namely in Seichodo in Ashiya City, and Nishihonmachi, Amagasaki City, as shown in Fig. 7(b) and (c), respectively. The ASE noise barrier is still erected as of 2019 [78,79] and has been in operation at least up till 2012 [80]. Aside from these instances, however, there is an absence of large-scale adoption of ANBs.

Active noise control at the receiver: Although noise control at the receivers' end is considered inefficient, it is usually the only means of control available to the receiver, in the context of environmental noise. As environmental noise mostly enters the building interior via façade openings such as windows, successful control of the noise through these openings will theoretically result in noise reduction within the entire

Table 3
A collection of active noise control applications in the built environment with experimental demonstrations and their estimated technology readiness levels (TRL).

Noise intervention zone	Targeted noise type	ANC control zone	ANC application	Reference	Reported noise reduction	Estimated TRL
Source	Construction[a]	Local	Construction machine exhaust	INC Engineering Co. Ltd [72]	19 dB at 103 Hz and 17 dB at 206 Hz	7–8
	Construction[a]	Local	Genset exhaust	Matsuoka et al. [74]	23 dB at error microphone (Idle) 17 dB at error microphone (40 kW load)	8–9
	Construction[a]	Global	Construction machine exhaust	Kobayashi et al. [87,88]	27.1 dB at error microphone 11.4 dB–16.8 dB 8 m away	8–9
	Construction[a]	Not stated	Construction machine exhaust	ANC-Labo [73]	21 dB (near machine) 17.7 dB (in building)	7–8
	Transformer	Shadow zone	Noise barrier	Zou et al. [25]	0.3–4.3 dBA below 400 Hz	6–7
	Transformer	Global	Virtual barrier	Tao et al. [26,27]	~18 dB	6–7
	Transformer	Global	Virtual barrier	Ying et al. [89] [c]	5 dBA in desired area	6–7
	Transformer	Not specified	Virtual barrier	Sonobex	6 dB (100 Hz); 13 dB (200 Hz) Overall (4.3 dBA)	8–9
Propagation Path	Construction[a]	Shadow zone	Noise barrier	INC Engineering Co. Ltd [48]	Virtually extends height of noise barrier by 3–5 m	8–9
	Road traffic[a]	Shadow zone	Noise barrier	Ohnishi and Saito [81] [c] Ohnishi et al. [82] Saito et al. [90]	3 dB–4.3 dB at pavement	8–9
Receiver	Road traffic[a] Train[a] Aircraft fly-by[a]	Room interior (Global)	Façade Element (Window)	Lam et al. [54] [c]	Traffic (100–1000 Hz): 8.67 dB; Train (100–1000 Hz): 10.14 dB; Aircraft (100–1000 Hz): 7.51 dB	5–6
	Aircraft fly-by[a] Motorbike[a] Road traffic[a] Compressor[a]	Room interior (Global)	Façade Element (Window)	Lam et al. [53] [c]	Aircraft (100–700 Hz): 5.76 dB; Motorbike (100–700 Hz): 4.84 dB Traffic (100–700 Hz): 4.56 dB; Compressor (100–700 Hz): 10.51 dB	5–6
	Real aircraft pass-by[a]	Room interior (Global)	Façade Element (Window)	Paimes et al. [91] [c]	~3 dB (0.2–0.16 kHz)	6–7
	Road traffic[a]	Not stated	Façade Element (Window)	Carme et al. [86]	15.5 dB (<300 Hz)	5
	Floor impact noise[b]	Room interior (Global)	Ceiling	Terai et al. [92]	3.8 dB (63 Hz octave band) ~10 dB (25 Hz peak)	3

[a] Environmental noise.
[b] Interior noise.
[c] Peer-reviewed.



(a) (b) (c)

Fig. 5. Operational demonstrations of (a) an active silencer prototype for the active control of noise at the exhaust of an excavator [72], (b) implementation of ANC at the exhaust of a crawler crane [73], and (c) an active control implementation at the exhaust outlet of electrical power generators [74].

(a) (b) (c)

Fig. 6. Active noise control implementation for (a) a 110 kV power transformer in Hunan, China [25,27], (b) two 110 kV power transformers in a semi-enclosed building in Guilin, China [26], and (c) at a transformer station in Poeldijk, South Holland, Netherlands [75].

(a) (b) (c)

Fig. 7. (a) An active noise barrier for mitigation noise from a construction site [48], the active soft edge [22,23,81,82] noise barrier along Route 43 in (b) Seichodo, Ashiya City, Japan [79], and (c) Nishihonmachi, Amagasaki City, Japan [78].

room interior. Traditional approaches to façade treatment for noise mitigation, such as protrusive (e.g. lintels, eaves, fins, balconies) and resonant devices, are predominantly passive and have limited noise control success for high-rise urban landscapes [50]. Recent implementations of plenum window designs have exhibited promising reductions for traffic noise, but at the expense of airflow [50,83].

Owing to both its effectiveness at mitigating low-frequencies and its compact nature, active noise control has been proposed as a promising solution for mitigating environmental noise through façade openings without affecting natural ventilation [29,52,54,84,85]. Recently, there has been proof-of-principle studies (TRL≈6) demonstrating the active control of environmental on an open, full-sized, sliding window [54] and an open top-hung window in a full-scale room [53], as shown in Fig. 8(a) and (b), respectively. At least one commercial entity has presented an ANC prototype for partially-open sliding windows (TRL≈5), as shown in Fig. 8(c).

The abovementioned applications and their publicly reported noise reduction performance, as well as their estimated TRLs are compiled in Table 3. Judging from the lack of commercial activity, implementation of ANC on noise barriers and façade openings are still challenging

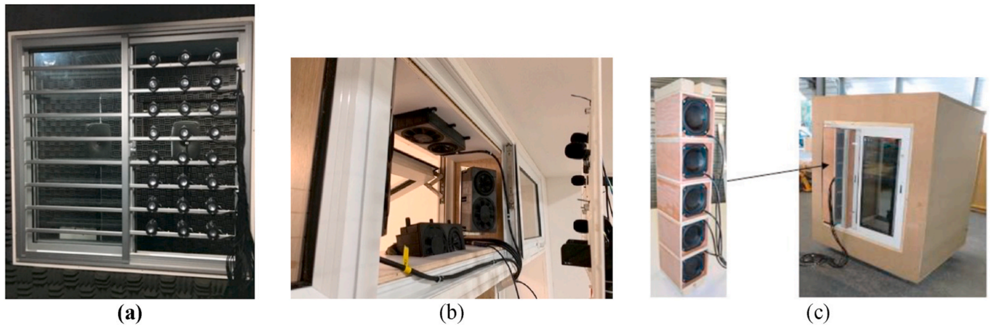


Fig. 8. (a) A 24-channel ANC system on a full-sized open sliding window in a mock-up room [54], (b) a 4-channel ANC system on an open top-hung window in a full-scale bedroom [53], a 5-channel ANC system on a scaled down partially open window [86].

technological endeavours. Their feasibility and implementation procedures are detailed in follow-up questions in sections 2.4 and 2.5, respectively. Moreover, the technological challenges and concerns on operationality warrants a deeper discussion, as presented in sections 2.7 and 2.8, respectively.

2.4. How to implement active noise control on noise barriers?

Answer: The ANC unit usually can be installed on the top or in the slit of the noise barriers. In that way, the ANC system can significantly reduce the low-frequency noise that leaks through or diffuses over the barrier.

Noise control in open space is normally achieved by noise reducing barriers. Noise barrier (passive control) is generally useful in the high frequency region but its performance is degraded at lower frequencies, owing to increased diffraction at low frequencies [27]. To reduce the diffracted sound and realize global noise attenuation behind the barrier, some passive devices have been installed along the top of the barriers [93,94]. These devices were designed to realize a sound absorbing boundary or the acoustic soft boundary at the top of the barriers. Here, the acoustic soft boundary refers to the situation where the sound pressure is zero at the boundary. In particular, the acoustic soft boundary is known to be able to reduce the diffraction sound remarkably [95,96].

However, it is difficult for passive devices to realize the acoustic soft boundary in a wide frequency range. Therefore, some active devices, also known collectively as active noise barriers (ANB), have been investigated. Active noise control (ANC) can not only realize the acoustic soft boundary, which can realize global noise attenuation behind the barrier, but is more effective in generating a quiet direction or zone in the target area behind the noise barrier.

There are two kinds of ANB, one for stable noise sources and another for multiple moving noise sources. Each of the abovementioned ANBs utilises distinct ANC systems, which creates an acoustic soft boundary to generate the quiet zone. It is worth noting that the ANB for multiple moving noise sources is also effective for stable noise sources, but not vice versa.

Fig. 9 shows ANB system for stable noise sources by realising an acoustic soft boundary at the top of noise barrier [96]. Although, in Fig. 9, the signal from the noise generator was used as the reference signal, generally, reference sensors (microphones) are set near the noise sources. Control speakers are installed between the noise sources and the noise barrier. Error sensors (microphones) are set at the top of noise barrier. This system is controlled by the ordinary multichannel feedforward filtered-reference LMS control algorithm (MCFxLMS) [13], which reduces the sound pressure at the top of noise barrier to realize an acoustic soft boundary. Fig. 10 shows the schematic of the ANB system for stable noise sources generating a quiet zone behind the barrier [97]. In this case, reference sensors are also set near the noise sources. Control speakers are installed at the top of noise barrier. And error sensors are

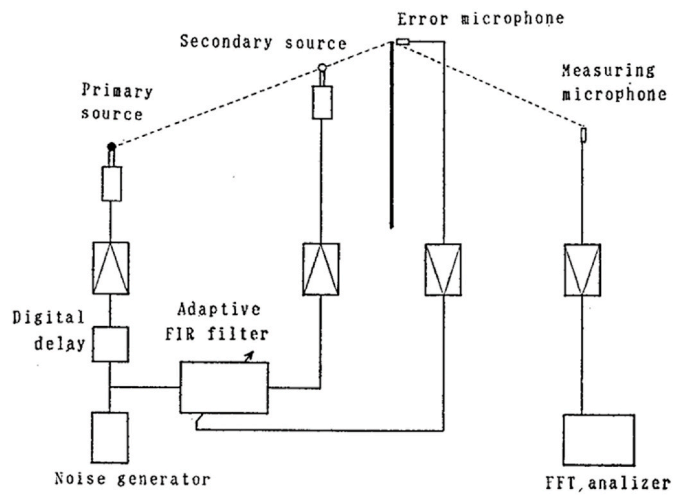


Fig. 9. Configuration of ANB system for stable noise sources by making the acoustic soft boundary at the top of barrier [96].

set in the target direction or zone. The distance between the control speakers should be shorter than half wavelength of highest sound frequency to be reduced. This system is also controlled by ordinary MCFxLMS algorithm. A commercialized version for construction machines is shown in Fig. 11 [48].

An Active Soft Edge (ASE) system was developed to realize the acoustic soft boundary at the top of barrier for multiple moving noise sources [23,81,82,90]. Fig. 12 shows configuration of the prototype ASE. ASE-cells are installed in a linear array at the top of noise barrier. Each ASE-cell has a control speaker with an error microphone affixed in front of it, and an analog control circuit. Here, the error microphone signal is always controlled to be zero by the analog feedback control method, regardless of the direction of primary sound propagation. Therefore, the sound pressure at the surface of ASE-cell continues to be minimised even if with multiple or moving primary noise sources. This implies that the acoustic soft boundary at the top of noise barrier is always realized for traffic noise. In Fig. 12 (a), an ASE-unit comprising of two 2-m long linear arrays of ASE-cells (total of 24 ASE-cells) is depicted. ASE-units can easily be installed on top of conventional noise barriers. It is important that the size of ASE-cell should be less than a quarter of the wavelength of the highest sound frequency to be reduced. And the lateral distance between the centres of ASE-cells along the barrier is also recommended to be less than a quarter wavelength. Active noise reduction performance of ASE had been measured in field tests as 3–5 dB below 1 kHz. ASE was also found to be effective for moving noise sources in the field tests [23,90]. ASE has been applied to two sections along a real road in Japan (Route 43 in Seichodo, Ashiya City [79] and Nishihonmachi, Amagasaki City [78]), as shown in Fig. 12 (b).

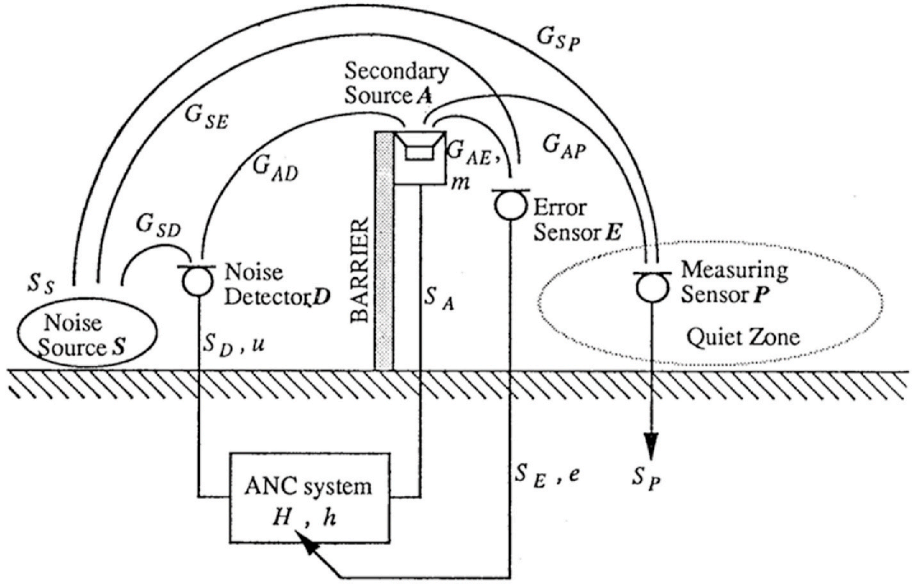


Fig. 10. Configuration of ANB system for stable noise sources by making quiet direction or zone [97].

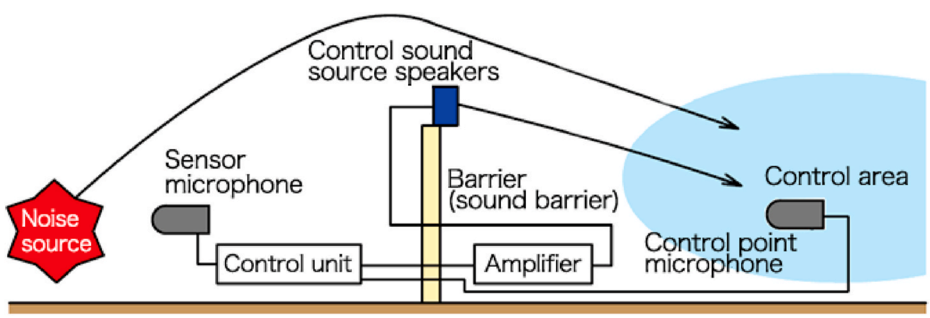


Fig. 11. Commercialized ANB system for stable noise sources by making quiet direction or zone [48].

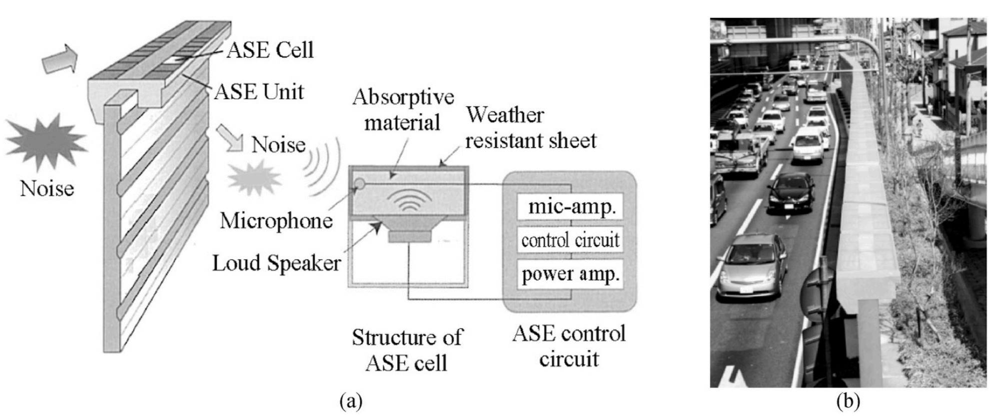


Fig. 12. (a) Configuration of Active Soft Edge (ASE) [23], (b) photo of ASE [23].

The noise reduction performance of the acoustic soft boundary by analog feedback control is limited in frequency range and in spatial zone. Then it has been proposed to realize the quiet zone behind noise barrier based on digital feed forward control for multiple moving noise sources [98,99], namely the 'Advanced Active Noise Barrier (AANB)'. The configuration of AANB is shown in Fig. Fig. 13. Here, active cells are installed in line at the top of noise barrier like ASE. Each cell consists of a reference microphone, a control speaker and a digital controller. The reference microphone is set just in front of the control speaker with very small distance compared with the wavelength of target sound just like as co-located. Each cell is individually controlled by a simple FxLMS feedforward control algorithm. Error microphones are temporally installed behind the noise barrier at the target direction or zone when converging the control filter. After the adaptive control filter is converged, the filter is fixed and the error microphones are removed.

Because the reference microphone and the control speaker is just like as co-located, AANB can reduce the sound propagated from any direction. That means AANB is supposed to be effective for multiple moving

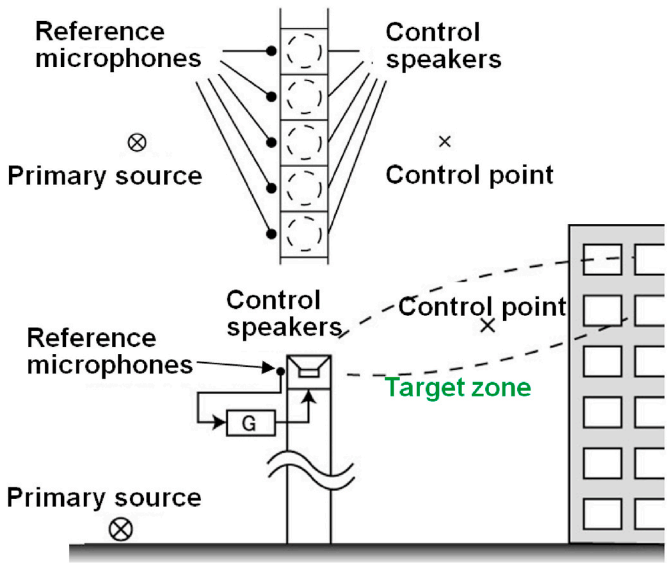


Fig. 13. Configuration of advanced active noise barrier (AANB) [99].

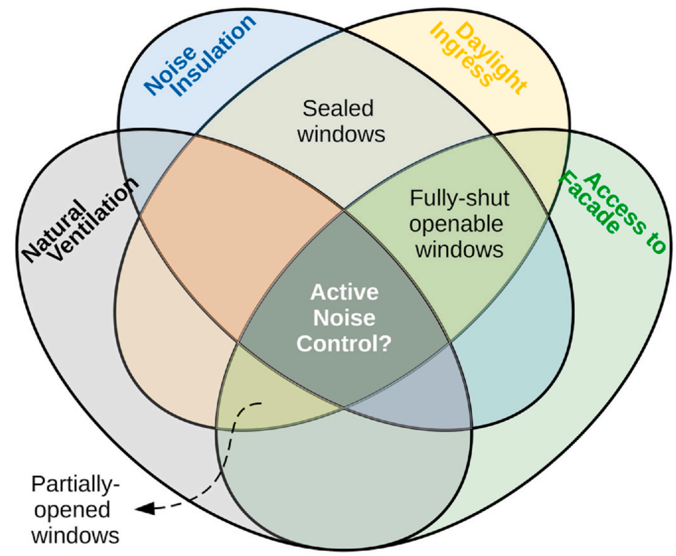


Fig. 14. Four-way Venn diagram representing four essential functions of openable windows for naturally-ventilated buildings [101,102].

sources like traffic noise. In order to satisfy the causality law between the reference microphone and control speaker in such short distance, very high sampling frequency was adopted to shorten *anti*-aliasing filter delay and sampling delay. Field Programmable Gate Array (FPGA) was used for establishing such high speed digital signal processing [100]. About 10 dB noise reduction was obtained in laboratory experiments of AANB [98,99].

2.5. How practically feasible is active noise control for façade openings?

Answer: Recent proof-of-principle demonstrations [53,54] have shown that with optimised placement of active elements and careful consideration on the window size and frequency upper bound for control, global noise reduction can be achieved within the entire room interior.

Since environmental noise enters the building interior predominantly through façade openings such as windows and ventilation openings, much emphasis has been placed on reducing the transmission of noise through these openings. In a domestic setting, there are generally four main functions of a window with varying levels of priority across cultures and geography, (1) noise insulation, (2) natural ventilation, (3) daylight ingress, and (4) access to the façade. Three main physical states of windows, i.e. sealed, partially-open, fully-shut but openable, are indicated in their respective intersections, as shown in the four-way Venn diagram of the four functions in Fig. 14. Increased demand for naturally-ventilated buildings has fuelled the search for innovative passive noise insulation devices that do not obstruct the flow of air, albeit to limited success [49,50]. Characteristically, active noise control seemingly appears to meet all four requirements [101].

Active control techniques have long offered the premise of compact low-frequency noise control without obstruction of air flow, as evidenced in air ducts [13,103]. Although there had been some investigations into the active control of noise through façade openings [104–106], the physical limits of active control for open apertures were only recently determined [27,30,101,107]. In general, active control sources producing the anti-noise (i.e. loudspeakers) are either distributed across the entire aperture, or mounted around the periphery, as shown in Fig. 15(a) and (b), respectively.

The choice between distributed-layout (DL) and boundary-layout (BL) strategies can be determined by evaluating their physical limits of control, obstruction to airflow, scalability with aperture size, and visual impact, as summarised in Table 4.

The low-frequency performance of DL and BL strategies are determined by the response of the actuators (e.g. loudspeakers) used. However, DL systems would generally require smaller actuators to minimise the overall visual occlusion, resulting in poor low-frequency performance [54]. On the other hand, the upper frequency limit of control is dependent on the separation distance between the control sources. For DL systems, the upper frequency limit of control is given by [30,107].

$$f_{upper} = \frac{c_0}{w(1+\sin\theta)}, \quad \theta \leq 90^{\circ} \tag{1}$$

where c0 is the speed of sound in air $\boldsymbol{w}$ is the separation distance between the control sources, and θ is the angle of noise incidence, as depicted in Fig. 15.

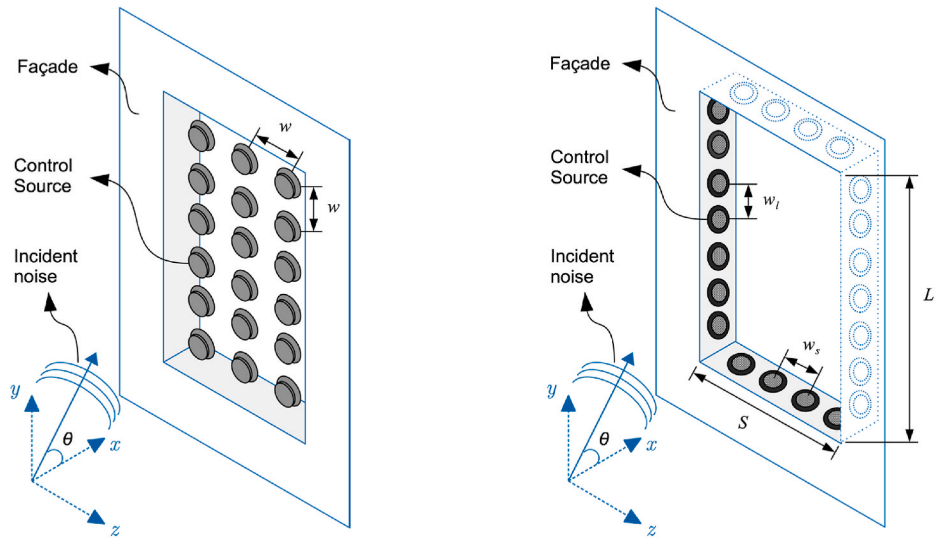
In BL systems, if the control sources are only located along both long edges of length L, then the upper frequency limit of control becomes where $f_{upper} = c_0/w_l$ is the separation distance between the control sources on the long side [27]. However, f_{upper} diminishes to $c_0/2w_l$ when the length of short edge, S, approaches wl. If the control sources are installed around the entire periphery, the upper frequency limit becomes. $f_{upper} = c_0/S$

It becomes apparent that the upper frequency limit of DL systems are sensitive to the noise incidence, whereas BL systems are largely unaffected. In contrast, DL systems appear to be more scalable with increasing aperture sizes, albeit at the expense of visual obscurity. The decision to adopt either the DL or BL ANC systems for open apertures lies is ultimately dependent on the users' priorities.

2.6. Is it possible to actively control noise in a large open space?

Answer: Active control of noise in a large open space usually necessitates the employment of a multitude of sensors and actuators, which constitutes a multichannel ANC (MCANC) system. In contrast, a single-channel ANC system only achieves local control, physically limited to a small noise control zone, measuring about a tenth of the wavelength in diameter around the error microphone [14]. Therefore, to gain the global control in an open space, the control sources should be ideally collocated with the noise source.

As mentioned in section 2.3, control at source is usually infeasible, especially in the complex built environment. An alternative method, spatial ANC [109–115], in which many secondary sources are located around the desired area, was proposed. According to Huygens–Fresnel principle [12,116,117], the wavefront of the noise can be regarded to be



(a) (b)

Fig. 15. An illustration showing anti-noise generating active control sources distributed (a) across [54], and (b) around the periphery [108] of the façade aperture, i.e. window opening.

Table 4
Comparison between distributed-layout and boundary-layout active noise control implementations on open apertures for natural ventilation.

	Distributed-layout	Boundary-layout
Lower frequency limit	Determined by response of actuators	
Upper frequency limit	Dependent on distance between control sources [107] $f_{upper} = \frac{c_0}{w(1+\sin\theta)}$, $\theta \leq 90^o$	Dependent on aperture size and control source layout [27] Control sources only on long sides: $c_0/2w_l \leq f_{upper} \leq c_0/w_l$ Control sources on all sides: $f_{upper} = c_0/w_s$
Influence of primary incidence on f_{upper}	Significant reduction at glancing incidences	Negligible
Airflow obstruction	Minimal	None
Scalability with aperture size	Yes	No
Visual impact	Obstructs	Obscure

composed of many tripole sound sources [14,118]. Hence, secondary sources can achieve noise cancellation inside an enclosure by counterbalancing these equivalent tripole noises at its surface. However, this technique also requires a large number of secondary sources, which undermines its practicality. Therefore, further research is required to realize spatial ANC in practice at reasonable cost.

2.7. Are there still technological challenges in the practical implementation of active noise control?

Answer: Owing to the physical-electroacoustic-digital nature of modern ANC systems, the maximum performance of an ANC system is usually limited by a myriad of issues in practice. After the physical optimisation of the control source and sensor arrangements, engineering decisions are required when selecting electroacoustic components that minimise active control performance degradation, while maintaining cost effectiveness. It is thus important to discuss these technological impediments (i.e. electroacoustic components, Algorithms, digital controllers) that are inhibiting the full potential of ANC. Due to the interconnectedness and interdependency of the ANC system components, this discussion have been organised in terms of their respective domains, i.e. acoustic, analog, digital as shown in Fig. 3.

2.7.1. Acoustic domain

Primary noise: Spectral and temporal characteristics of the primary noise to be controlled usually dictates the physical arrangement and selection of the electroacoustic components, as well as the selection of ANC Algorithms for effective control. On the spectral front, the upper frequency limit of control is heavily influenced by the arrangement of control sources and sensors, as exemplified in Section 2.5. Performance at the lower frequencies is dependent on the control source characteristics. The desired frequency bandwidth to be control affects the algorithmic selection, wherein feedback ANC structures are only suitable narrowband noise control, whereas the feedforward and hybrid ANC structures can control both narrowband and broadband noises [13].

Temporal variations in the primary noise, e.g. rapid changes in amplitude or noise type, affects the control performance or convergence of an adaptive ANC system. Algorithmic innovations to alleviate these challenges must be developed with real-time operation in mind to be of practical use. For instance, the ANC system can be pre-tuned to specific control profiles for different noise scenarios. A mechanism is then devised to invoke the optimal control profile upon detecting changes in the noise signal, also known as selective fixed-filter ANC [46,119].

Acoustic sensors: Apart from physical factors, such as control source and sensor arrangements, characteristics of electroacoustic components (e.g. actuator and sensor frequency response) inherently limit the bandwidth of the controlled noise. Whereas control of narrowband noise is usually achieved with non-acoustic sensors, such as accelerometers and tachometers, acoustic sensors, i.e. microphones, are usually employed for broadband noise control. The emergence of microelectromechanical systems (MEMS) microphones have drastically reduced the cost of multi-microphone implementations, along with an unparalleled electroacoustic performance and stability in a miniature form factor, as compared to traditional electret condenser microphones [120]. As the quality of the reference signal is vital to the ANC performance, acoustic feedback or wind noise picked up by the reference microphones must be managed (e.g. shielding, compensating filter).

In the conventional ANC system, the error microphone is the critical component that decides the actual position of the noise cancellation zone. However, in some real scenarios, it is impractical to place the error microphone in the desired position, such as at the eardrums. To solve this issue, the virtual microphone [121–123] was proposed to predict the sound pressure at desired virtual positions based on analytical models of the acoustic path from physical microphones placed at more convenient locations. The active control performance is thus sensitive to the accuracy of the models employed. An extension of this method is the remote microphone technique that applies observation filter to estimate the disturbance at the virtual microphone from the primary noise at the physical microphone [124,125]. This observation filter is essentially the transfer function from the physical microphone to the virtual microphone position that was measured in advance. This method is increasingly used in automobile cabin ANC to control noise at the headrest positions from microphones embedded in the roof [18]. Another technique is the virtual sensing ANC (VS-ANC) [126] that first pre-trains an auxiliary filter, which represents the difference between the physical and virtual position, in a training stage. This auxiliary filter then assists the adaptive algorithm to implement noise cancellation at the desired virtual position in the control stage. This VS-ANC technique has been successfully realized in headphones [127] and open windows [128]. As the remote microphone technique is sensitive to changes in the transfer path to the physical microphones, whereas auxiliary filter technique is sensitive to uncertainties in the reference signal [129], it is important to tailor the solution to the active control problem.

Acoustic actuators: On the contrary, acoustic actuators, i.e. loudspeakers, have yet to experience such industry-changing innovations. Omnipresent urban environmental noise is often loud and dominant in the low frequencies, which requires traditional loudspeakers with a large diaphragm and cabinet volume to generate an identical anti-noise. This size requirement complicates the ANC system design for applications in the built environment, e.g. noise barriers, transformer stations, and especially when airflow should be unobstructed, e.g. windows, exhaust. Although there are some promising loudspeaker innovations on the horizon that would significantly improve power efficiency and the frequency response of speakers with the adoption of graphene [130, 131], widespread commercialisation of graphene is still hampered by mass production issues and cost [132,133].

2.7.2. Analog domain

To mitigate broadband disturbances, a feedforward ANC system is usually employed. However, once the acoustic and electronic delays in the feedforward system exceed the acoustic propagation time in the primary path, the causality constraint would be violated [134], failing to cancel the broadband noise in time [135]. In a digital feedforward ANC system, the latency of analog-to digital and digital-to-analog converters constitute bulk of the electronic delay. There are different types of ADCs and DACs, each having different latency times and associated trade-offs, as shown in Table 5. Among these ADCs and DACs, the SAR ADC and R-2R Ladder DAC appear to be the most suitable for ANC applications due to their balance between latency and resolution. Furthermore, in time critical feedforward configurations, e.g. collocated reference sensors and control sources, the delay incurred in the power amplifiers could become significant. Hence, traditional class AB amplifiers are preferred over the energy-efficient class D amplifiers for time critical ANC systems.

Table 5
Summary of latency and trade-off characteristics of analog-to-digital converters (ADCs) and digital-to-analog converters (DACs).

Component	Type	Latency	Critical characteristics/ trade-offs
Analog-to-digital Converter (ADC)	Successive Approximation Register (SAR)	Low	Good speed/ resolution ratio
	Delta-Sigma	High	High resolution
	Dual Slope	Average	Accurate, inexpensive, low speed
	Pipelined	Lowest	Very fast, limited resolution
	Flash	Low	Fastest, low bit resolution
Digital-to-analog converter (DAC)	Summing Amplifier	Low	High speed, low resolution
	R-2R Ladder	Low	High speed, average resolution
	PWM	High	Low speed, high resolution
	Delta-Sigma	High	High resolution

2.7.3. Digital domain

Algorithms: Following from the discussion above, the controller algorithm used in ANC is one of the final impediments to achieve maximum noise control performance in the hierarchy of practical ANC system design [51]. For example, due to the slow tracking capability, the conventional filtered-reference least mean square (FxLMS) algorithm [136–138] has worse noise reduction in nonstationary noise. In contrast, the fixed-filter method shows better performance on quick-varying noise at the expense of poorer noise reduction level compared to its adaptive-filter counterpart.

The adaptive control technology bestows ANC with the ability to handle the variations of noise and changes in the acoustic environment, at the risk of introducing instability in the system. During continual operation, the feedback effect from the control source to the reference microphone, output saturation distortion due to an overdriven amplifier, and the changes in the secondary path, all contribute to the instability of the adaptive algorithm.

Computational cost: To realize an adaptive algorithm, an ANC system usually requires a powerful controller, which could dominate bulk of the hardware cost. If we assume that a multi-channel ANC system has I reference sensors, J secondary sources, and K error sensors, and the control filter and secondary path estimate have L and LS taps, respectively, the number of multiplications and additions in the multichannel FxLMS Algorithms is given by

$$N_0 = IJL + IJK(L+1) + IJKL_s, \tag{2}$$

as shown in Table 6 [139].

Many devices, such as the microcontroller (MCU), digital signal processor (DSP), and field-programmable gate array (FPGA), have been employed to implement adaptive Algorithms in an ANC system, as shown in Table 7. Among these processors, the MCU costs the least but is only capable of executing the single-channel FxLMS algorithm with short filters. In contrast, the FPGA has the most powerful processing ability, but its high price and complex programming impedes its practical adoption. In most ANC applications, a DSP appears to be a balanced choice for its performance and reasonable price. It should be noted that, the premise of application-specific integrated circuit (ASIC) should not be discounted as a suitable candidate to replace these expensive processors in the future. The abovementioned technological hurdles and their recommended solutions are summarised in Table 8.

Table 6
The computational complexity of a MCFxLMS system with I references, J outputs, and K errors.

Operation	Number of additions and multiplications
Adaptive filter	IJL
Coefficients update	$IJK(L+1)$
Filtering reference	$IJKL_s$

Table 7
A summary of adaptive ANC implementations on real-time platforms.

Controller		L	LS	Algorithm	Data width (bits)	Sampling rate (Hz)
Architecture	Platform					
DSP	TMS320C25 [140]	64	64	FxLMS (FB)	16	8000
	TMS320C50 [141]	16	256	FxLMS (FB)	16	19200
	TMS320C6711 [142]	–	–	FxLMS (FB)	32	8000
ARM	STM32F407 [143]	32	32	FxLMS (FB)	32	4000
MCU	PIC24H [144]	20	20	FxLMS (FB)	32	10000
	Arduino DUE [145]	–	–	FxLMS (FF)	32	4096
IC	VLSI [146]	24	64	FxLMS (FF)	16	96000
x86	Opteron [147]	1024	1024	FxLMS (FF)	32	4096
	i7-3610 [148,149]	512	256	4-channel MCFxLMS (FF)	32	16000
	E5-2618 [149]	512	256	Two-gradient FxLMS (FF)	32	16000
FPGA	Virtex-II [150]	–	1024	Normalized FxLMS (FF)	32	40000
	EP2S180F [151]	64	–	LMS (FF)	16	–
	XC7Z010 [152]	40	40	Systolic FxLMS (FF)	32	–
	CompactRIO [153]	6	–	Notch filter (FF)	32	20000
	Kintex-7 7K325 [154]	200	200	4-channel MCFxLMS (FF)	32	24000
	Kintex-7 7K325 [155]	200	200	24-channel MCFxLMS (FF)	32	25000

Note: FB and FF denote feedback and feedforward ANC system structures, respectively.

Table 8
Summary of technological limitations of practical active noise control categorised by domain and recommendations for future research.

Domain	Sub-domain	Scenario/ Limitation	Recommended and Envisioned Solutions
Acoustic	Primary noise amplitude	Varying with time	Algorithmic innovations
		Large amplitude	Actuator and sensor optimisation, algorithmic innovations
	Primary noise frequency	Lower frequency limit	Control source innovation/ customisation for high-amplitude low-frequency noise
		Upper frequency limit	Fully characterise physical limits
	Primary noise type	Varying with time	Algorithmic innovations on selective fixed-filter implementations
	Acoustic sensor	Interference	Shielding or compensation due to wind noise or acoustic feedback
	Acoustic actuator	Output power, physical size, power efficiency	Customisation and careful optimisation (near-term). Requires significant innovation (long-term)
Analog	A/D and D/A conversion	Latency, signal quality	Use low-latency components (i.e. successive-approximation register ADCs, class AB amplifier)
Digital	Algorithms	Adaptive or fixed-filter	Innovations in selective fixed-filter approach
	Computational cost	High computational complexity	Algorithmic innovations and ASIC implementation

2.8. What are the operational concerns limiting the deployment of active noise control in the built environment?

Answer: There are some common underlying operational concerns that contribute to the resistance towards implementation of ANC in the built environment.

Cost: Introduction of a new technology into an existing product carries additional risk and cost. Hence, the physical limits of control for the intended application should first be established to gauge the feasibility of ANC implementation. Mass-producibility is also important to reduce the bill of materials (BOM) cost, which mainly consists of the controller, actuators, and sensors [18,156]. The cost of the controller could be significantly reduced by adopting a system-on-a-chip (SoC) design, as well as adopting industry standard interfaces where possible. A modular design of the actuator and sensor components also allows for simpler manufacturing and lower maintenance costs.

Privacy: The requirements of microphones in most ANC applications raises the concern on the invasion of privacy. Since ANC computes the anti-noise locally, the privacy risk is minimal without data retention and external transmission, unlike smart speakers [157].

Longevity: Although consumer implementations of active noise control (i.e. headsets, earbuds) are not optimised for longevity, there are ANC systems that have been in operation for many years. This is exemplified in the ANC units for propeller aircraft manufactured by Ultra Electronics Limited [158], whereby their ISO 7137 avionics-compliant systems have accumulated 3.2 million flight hours as of 2014 [159]. Increased electrification of automobiles have also improved the longevity of automotive electronics to meet the expected operating life of more than ten years [160], providing a reliable infrastructure for digital ANC applications [18,156]. Hence, robust ANC systems for built environment applications with wide operating ambient temperature and humidity ranges are not unfathomable as evidenced in aircraft and automobile ANC applications.

2.9. Is there a synergy between active noise control and the soundscape approach?

Answer: Yes.

The notion of soundscape represents a paradigm shift away from noise control methodologies and policies, which are largely based on sound pressure level measurements [161,162]. Soundscape is defined by the International Organization for Standardisation as the “acoustic environment as perceived or experienced and/or understood by a person or people, in context” [163]. In essence, soundscape is a perceptual construct that embodies individual experiences and other non-acoustical factors that influences the perception of one’s interpretation of the acoustic environment.

At first glance, active noise control is naturally associated with traditional noise control as it usually tuned to minimise the sound pressure of an unwanted noise at a desired location. Interestingly, there is a notable sub-field of perceptually-driven ANC research that optimises the psychoacoustic characteristics of the residual noise to enhance the overall sound quality [103,164]. Psychoacoustics is “the science that studies the statistical relationships between acoustical stimuli and hearing sensations” [165], which is usually represented with objective parameters, such as loudness [166,167], sharpness [168], tonality [169,170], roughness [171,172], and fluctuation strength. Psychoacoustic ANC has been traditionally applied to automobiles to “shape” the residual noise during active control to achieve desired sound profiles, i.e. active sound profiling [173–175], or optimisation of cabin sound quality based on psychoacoustic parameters [176–179].

Moreover, there has also been some interest in selective cancellation techniques for practical ANC applications such as fixed-filter selection optimised for different noise types [46,119,180]. One active use case is the incorporation of these dynamic active noise control profile switching capabilities by ANC system-on-a-chip providers [44] for consumer ANC headsets. These selective techniques can be incorporated into ANC applications (e.g. for open windows) to selectively attenuate the most annoying noise sources, while enhancing or augmenting desired sounds (i.e. natural sounds) not unlike active sound profiling.

There is a definite possibility of incorporating urban soundscape predictive models [181,182] into the objective functions of ANC implementations in the outdoor built environment, for instance for ANC on construction machines and active noise barriers. Potentially, ANC could play a pivotal role in the emerging field of indoor soundscaping for naturally-ventilated buildings [183,184] by providing the element of controllability [53], an important criteria for adaptive acoustic comfort [184]. At present, ANC could also be applied in tandem with the current soundscape approach, in which the unwanted noise is first identified and then controlled, ideally at source, with active means.

2.10. What are the future opportunities for wider applications of active noise control?

Answer: The inclusion of sensors and actuators in active noise control systems appears primed for integration into a city-wide Internet-of-Things (IoT) infrastructure, whereby active noise monitoring and control can be augmented with machine/deep learning Algorithms for noise event detection, classification, and localization to apply the most relevant noise control strategy in that moment. For example, with wireless sensing, an IoT-ANC system can receive advanced information of the noise source, which affords more time for a quicker response and adjustment of the control filter to handle temporally- and spatially-varying noise sources in the desired quiet zone.

A centralized multichannel ANC system can usually achieve excellent noise reduction performance, at the expense of higher implementation cost. In contrast, decentralized multi-channel ANC system, which can be easily scaled and maintained but with some loss in noise reduction performance, is seemingly a better approach to generate a larger zone of quiet. With the integration of IoT capabilities, information exchange from these decentralized multi-channel ANC systems can also provide some smart noise mitigation features to better control noise in different noise control regions. Furthermore, with the availability to capture environmental noise data through acoustic sensors, many smart AI models can be trained to better understand our urban environment (through noise scene analysis, noise event detection and localization, and noise source separation), and devise the most suitable noise mitigation technique under a given environmental and weather conditions. We are already seeing some of the environment-awareness intelligence that is being baked into commercial ANC headphones, and there will be more research opportunities in harvesting our environmental noise data for a better noise mitigation in our environment.

3. Conclusions

In conclusion, we outlined key questions on how ANC has been applied to the built environment, with the emphasis on their TRLs in applying to noise control at the source, noise path and at the received end. However, there are still gaps that prevent ANC from widespread adoption in the built environment. This article described several practical and technological limitations due to the placement of secondary sources; reference and error sensing microphones; processing platforms; and electro-acoustic component technologies. Several new research findings and trends in using artificial intelligence and perceptual approaches in ANC point to innovative attempts that have the potential to overcome these practical limitations and thus, lead to widespread adoption of ANC systems in the built environment.

Expertise of the authors on the topic

Dr. Bhan Lam received the B.Eng. (Hons.) and Ph.D. degrees both from the School of Electrical and Electronic Engineering, Nanyang Technological University, Singapore. During his Ph.D., he established the physical limits of active control for controlling noise through open apertures, and published a proof-of-principle study in Nature Scientific Reports. He is currently a research fellow at the same institution leading the effort in developing tools and systems for augmenting urban soundscapes. In 2015, he was a visiting postgrad in the signal processing and control group at the Institute of Sound and Vibration Research, University of Southampton, UK. He has authored more than 40 refereed journal articles and conference papers in the areas of acoustics, soundscape, and active noise control.

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He is a Fellow of the Audio Engineering Society (AES), a Fellow of the Institute of Engineering and Technology (IET), and a Senior Member of the IEEE. He served as an Associate Editor of the IEEE/ACM Transaction on Audio, Speech, and Language Processing (TASLP; 2012–15) and was presented with an Outstanding TASLP Editorial Board Service Award in 2016. He also served as the Associate Editor for the IEEE Signal Processing Letters (2015–19). He is currently serving as a Senior Area Editor of the IEEE Signal Processing Letters (2019–); Associate Technical Editor of the Journal of Audio Engineering Society (JAES; 2013–); Editorial member of the Asia Pacific Signal and Information Processing Association (APSIPA; 2011–) Transaction on Signal and Information Processing; Associate Editor of the EURASIP Journal on Audio, Speech and Music Processing (2007–).

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Graduate School of Engineering of Kyoto University in 1972. He worked for Takasago R&D Center of Mitsubishi Heavy Industries, Ltd. for 30 years until 2002. During this period, he had participated in many kinds of noise control jobs of various machines, e.g. air-conditioners, construction machines, vehicles and power plants. He also researched and developed various passive and active noise control techniques. He received the degree of Doctor of Engineering from Himeji Institute of Technology in 1990. In 2002 he moved to Tottori University as a professor in Department of Mechanical and Aerospace Engineering. From 2013 to 2018 he had been a Special Professor of Graduate School of Engineering in Tottori University and from 2013 to now he is the president of N. lab. which is a private company of machinery noise consulting. His research interests are active noise control, aeroacoustics, duct acoustics and machinery noise, especially in application fields. His current research interests are decentralized active control system such as Active Noise Barrier and Active Acoustic Shielding and some passive sound insulating techniques using light membrane. Professor Nishimura has published more than 75 papers and 13 books as a co-author. He also obtained over 40 patents. He is a fellow of JSME (the Japan Society of Mechanical Engineers). He received The Award of Research Achievement from the Environmental Engineering Division of JSME in 1999 on "Research on Aerodynamic Noise" and The Award of Engineering Development from ASJ (The Acoustical Society of Japan) in 2005 on "Active Soft Edge Noise Barrier".

Prof. Stephen Elliott graduated with joint honours in physics and electronics from the University of London, in 1976, and received his PhD from the University of Surrey in 1979 for a dissertation on musical acoustics.

He was appointed Lecturer at the Institute of Sound and Vibration Research (ISVR), University of Southampton, in 1982, was made Senior Lecturer in 1988, Professor in 1994, and served as Director of the ISVR from 2005 to 2010. His research interests have been mostly concerned with the connections between the physical world, signal processing and control, mainly in relation the active control of sound using adaptive filters and the active feedback control of vibration. This work has resulted in the practical demonstration of active control in propeller aircraft, cars and helicopters. His current research interests include modular systems for active feedback control and modelling the active processes within the cochlear.

Professor Elliott has published over 350 papers in refereed journals and 700 conference papers and is co-author of *Active Control of Sound* (with P A Nelson 1992), *Active Control of Vibration* (with C R Fuller and P A Nelson 1996) and author of *Signal Processing for Active Control* (2001). He is a Fellow of the Acoustical Society of America, was jointly awarded the Tyndall Medal from the Institute of Acoustics in 1992 and the Kenneth Harris James Prize from the Institution of Mechanical Engineers in 2000. He was made a Fellow of the Royal Academy of Engineering in 2009.

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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