A new era for applications of active noise control

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ABSTRACT

The fundamental theories and methods of active noise control (ANC) have become well established over the last 30 years, so fewer academic research projects on ANC are funded nowadays. However, applications of the technology are entering a new golden era with greater numbers of companies investigating the applications of noise control in their products. One good example is the successful application of ANC on Apple's iPhone 5 to increase speech quality in communication by cancelling ambient noise. This paper discusses a number of ANC projects that we have conducted over the last ten years with emphasis on the various challenges encountered in the applications of ANC. Aspects covered include acoustical design methods, recently developed adaptive control algorithms, new control hardware and systems, and new applications. The projects discussed include active control of transformer noise, ANC in natural ventilation windows, and ANC in a communication chassis. Unlike our previous research, all these projects are funded by industry bodies, and their aims are not to perform academic research, but to develop commercial products.

Keywords: Active control, Applications I-INCE Classification of Subjects Number(s): 36.4, 37.7

1. INTRODUCTION

Active noise control (ANC) is a method for reducing existing noise via the introduction of controllable secondary sources to affect generation, radiation, transmission, and reception of the original primary noise source. ANC can provide better solutions to low frequency noise problems than current passive noise control methods when there are weight and volume constraints. It also provides an alternative noise control solution to applications where current passive noise control methods cannot be applied. The fundamental theories and methods of ANC have become well established over the last 30 years [1–4]. However, successful industry and civil applications of the technology are still limited to some specific cases, such as headsets and earplugs, propeller aircraft, and cars [5–7].

With the successful application of ANC technology on the iPhone 5 by the Apple Corporation to increase speech quality in communication by cancelling ambient noise [8], an increasing number of companies are becoming interested in the technology and are beginning to investigate its applications in their products. Furthermore, the applications are no longer limited to the field of noise control, with more emerging in other fields such as the telecommunications and IT industries. For example, speech enhancement in noisy environments can be treated and solved as a special case of an ANC application. With better electronic hardware and digital signal processing algorithms, and larger market driving force, it appears that the theory, methods, and technology of active noise control are being pushed beyond their original limits and that a new era of applications is coming.

The design of an ANC system is not yet simple, however. Typically, it is a multi-variable optimization process and it can be divided into the following four stages [3, 9]. First, analysis of the physical system is necessary to determine the fundamental physical limitations of active control in the given application. Second, the optimum performance must be calculated using different control

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strategies with measurement data taken from the physical system. Third, a simulation of different control strategies should be performed using data from the physical system under a variety of operating conditions. Finally, a real-time controller must be implemented and the system must be tested under all conditions to ensure its performance, robustness, and durability.

This paper discusses several ANC projects that we have conducted over the last decade, emphasizing the various challenges encountered in ANC applications. Topics covered include acoustic design methods, recently developed adaptive control algorithms, new control hardware and systems, and new applications. Unlike our earlier academic research, all these projects are funded by industry bodies and their aims are not to perform academic research, but to develop commercial products.

2. RECENT PROGRESS OF ACTIVE NOISE CONTROL

2.1 Acoustical Design

In practical applications of ANC systems, such as that for transformer noise, there is typically ground and walls located around the noise sources. These reflecting surfaces may make the primary noise distribution more complicated and affect the actual performance of the ANC system. It has been found that the output power of two point sources located near a reflecting surface is dependent upon the system orientation angle, and that vertical arrangements of the ANC system can produce 14 dB more power reduction than horizontal arrangements [10]. Thus it is interesting to investigate whether it is possible to deliberately design some reflective surfaces around an ANC system that will enable the construction of a hybrid passive and active control system, so that the performance of the existing ANC system can be improved or the number of control sources of a multi-channel ANC system can be reduced without loss of noise control performance.

Table 1 shows the total sound power of a primary source and a multi-channel ANC system with and without 1 or 2 reflecting surfaces, where 0* stands for the evenly distributed configuration, and the search number stands for the searching generation of the genetic algorithm used to obtain the minimum output power of the ANC system by optimizing the distribution of the control sources [11]. In the simulation, the primary source is a point source located at (0 m, 0.005 m, 0.005 m) radiating tonal sound at 100 Hz and 200 Hz in free field with a sound power level of 90 dB. All control sources are distributed on the spherical surface of radius 1.0 m centered at the position of the noise source. When the control sources are evenly distributed on the spherical surface, the noise reduction can be achieved by the system in free field is about 20 dB with 9 control sources at 100 Hz and 10 dB with 25 control sources at 200 Hz.

Table 1 – The total sound power of a primary source and a multi-channel ANC system.

Search No.	100 Hz			200 Hz		
	Free field, 9 control sources	1 reflecting surface, 6 sources	2 reflecting surfaces, 3 sources	Free field, 25 control sources	1 reflecting surface, 12 sources	2 reflecting surfaces, 8 sources
0*	70.5	78.9	81.4	82.5	86.6	89.1
1	75.6	67.0	67.4	82.5	82.0	82.8
2	73.1	66.2	66.2	80.1	79.5	81.3
3	69.2	65.8	65.5	79.5	78.8	78.7
4	67.1	64.6	65.2	78.6	75.9	76.8
5	64.5	63.5	64.9	77.8	74.4	76.0

It is clear from Table 1 that introducing reflective surfaces can reduce the number of control sources after the system is optimally arranged. Nine control sources in the free field, six control sources in half the space, and three control sources in a quarter of the space can obtain a sound power reduction of more than 25 dB at 100 Hz. Twenty-five control sources in the free field, twelve control sources in half the space, and eight control sources in a quarter of the space can obtain around 14 dB of sound power attenuation at 200 Hz. Thus, the number of control sources of a multi-channel ANC system can be significantly reduced by introducing a reflecting surface with the optimal arrangement.

2.2 Algorithms

The adaptive filters in ANC systems differ from other common adaptive filters in the existence of cancellation paths, which are transfer functions between the outputs of adaptive control filters and error sensors. Cancellation paths play a critical role in ANC systems, and the most commonly used filtered-*x* LMS (FxLMS) algorithm takes them into account by filtering the reference signal with an estimate of the cancellation path transfer functions, which are often modeled on-line or at regular intervals in order to maintain the stability of the system. There are many methods for on-line cancellation modeling, such as the method that injects an uncorrelated signal into the cancellation path with a standard system identification approach, and the method that uses the control signal with an extended system identification approach. Instead of establishing an explicit cancellation path model with these mentioned methods, there are also several active control algorithms that do not need an explicit model of the cancellation path. Figure 1 shows a block diagram of the direction search LMS algorithm, which is one such algorithm [12]. In the direction search LMS algorithm, the standard LMS algorithm is adopted to update the adaptive filter coefficients directly with the reference signal by automatically choosing a proper update direction based on monitoring the excess noise power [13].

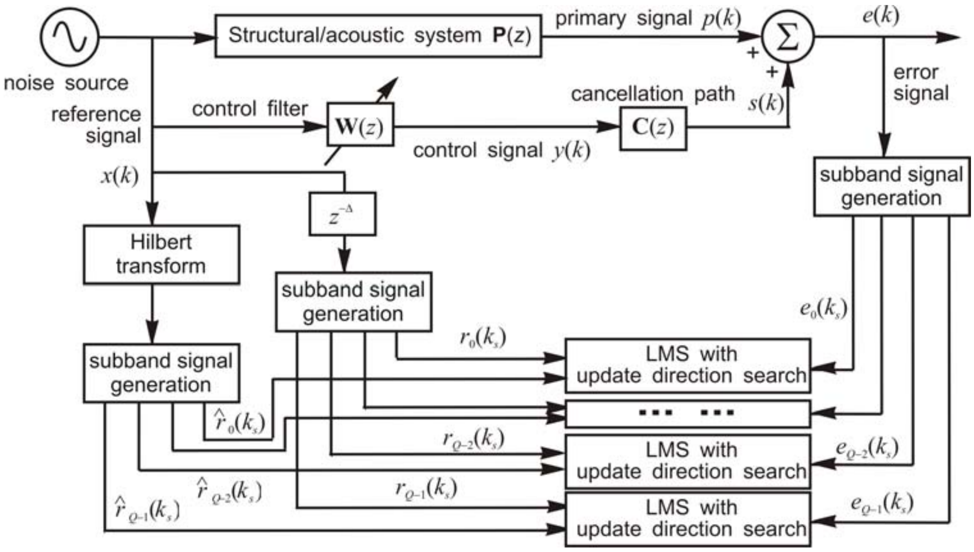


Figure 1 – Block diagram of the broadband ANC algorithm without cancellation path modeling.

The system consists of five parts: modified reference signal generation, subband signal generation, the subband LMS update direction search, the full-band adaptive coefficient update, and the full-band control signal generation (control filtering). The number of subbands depends on the properties of the cancellation path transfer function, which should be sufficient large to ensure that the maximum phase change of the transfer function in each subband is less than 90°. To reduce the number of subbands, the group delay of the cancellation path must first be roughly estimated. This is used to generate the first modified reference signal by delaying the reference signal with the same amount of delay. The second modified reference signal is obtained using the Hilbert transform to generate a signal that is 90° out of phase with the first modified reference signal.

Figure 2 shows the experimental results of the two algorithms in an ANC system in a duct, where the terminal condition at one end changes from absorption, open, closed, open, to absorption again [12]. For the FxLMS algorithm, the cancellation path model used in the control filter update is the one with the absorption end, so the noise quickly reduces in the first and fifth stages (absorption end), but does not attenuate any further from the second to fourth stages (open, closed, and open ends). For the broadband ANC algorithm without cancellation path modeling shown in Figure 1 (named ‘Subband’ in Figure 2), four subbands are used to control the band limited noise from 100 Hz to 500 Hz.

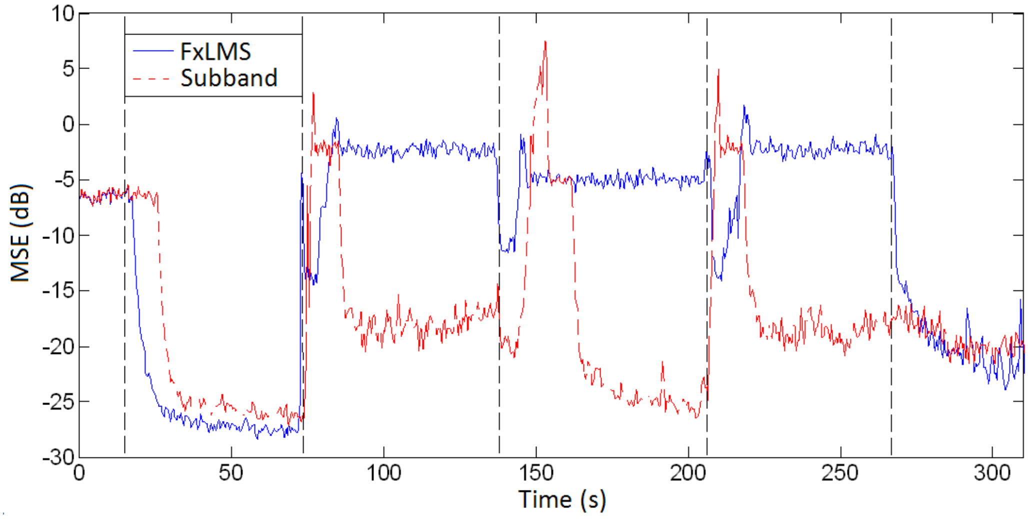


Figure 2 – The mean square error of an ANC system in a duct with the FxLMS algorithm (FxLMS) and the broadband ANC algorithm without cancellation path modeling (Subband) under different terminal conditions from absorption, open, closed, open, to absorption again, where, for the FxLMS algorithm, the cancellation path model used in the control filter update is the one with the absorption end.

The experimental results show that the direction search LMS algorithm can converge under all terminal conditions. Although its convergence speed may be slower than the FxLMS algorithm with the correctly estimated cancellation path model, the noise reduction it achieved is almost the same as that of the converged FxLMS algorithm. The direction search LMS algorithm does not require the generation of extra noise to perform cancellation path modeling. It is simple and compact for implementation, so it is especially suitable for low-cost mass-production applications.

In some applications where the primary noise cannot be directly observed or there are too many primary noise sources to obtain a reference signal economically, feedback ANC systems have to be used. Feedback ANC systems can be classified into two types: non-adaptive systems and adaptive systems. The former achieves noise reduction by designing the fixed controller to yield a high gain over the frequency band of interest but lower gain at other frequencies. However, stability and robustness problems may arise under various conditions, such as non-stationary primary noises and an uncertain secondary path. The most commonly used adaptive feedback system is the internal model control (IMC)–based structure, which regenerates the reference signal by filtering the secondary signal with the estimation of the secondary path and adding the error signal. This adaptive feedback system can be viewed as an adaptive feedforward system, so the widely used FxLMS algorithm can be directly applied for adaptation of the control filter.

When using the IMC-based adaptive feedback system, the secondary path is usually modeled by an FIR filter with hundreds or even thousands of coefficients. Filtering the secondary signal through the estimated secondary path is a heavy burden on real-time controllers. Figure 3 shows a block diagram of the simplified adaptive feedback (SimpAFB) ANC system, which adopts the error signal directly as a reference signal [14]. Compared with IMC-based systems, the proposed system has two advantages. First, its computational load is less, owing to the elimination of the convolution operation required for generating the reference signal. Second, current commercially available active controllers are typically only embedded with the FxLMS algorithm, so the proposed system can be easily implemented by feeding the error signal directly to the reference input of the controller.

Figure 4 shows the steady-state power spectral density of the error microphone signal before and after real-time control. The results show that the performance of the SimpAFB system almost matches that of the IMC system. For the non-adaptive feedback ANC system (H_2H_∞), when the primary noise changes from 250–300 Hz to 250–350 Hz, the control filter must be re-designed. Repeated attempts are often required to obtain a satisfactory controller in the design procedure. Meanwhile, the SimpAFB system can be implemented by simply connecting the input of the reference signal to the output of the error sensor in an adaptive feedforward ANC system, without any modifications of the hardware architecture. Even when the primary noise changes, the SimpAFB system does not require many modifications, except a few parameters like the adaptive step size and leakage coefficient.

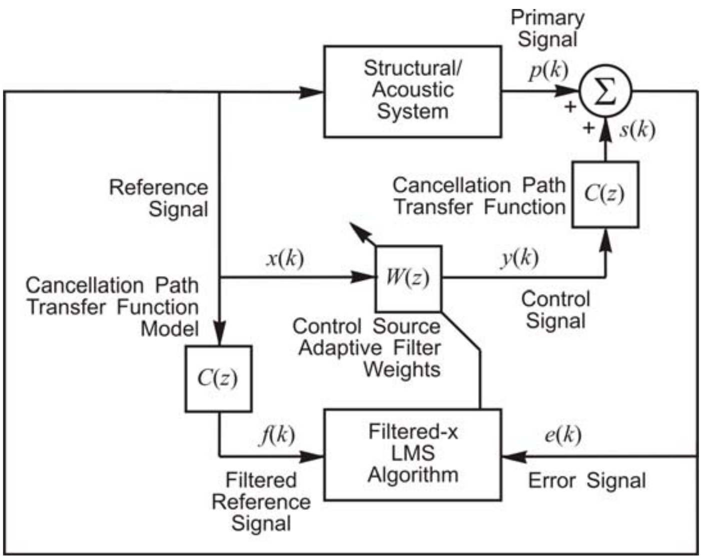


Figure 3 – Block diagram of the simplified adaptive single-channel feedback ANC system.

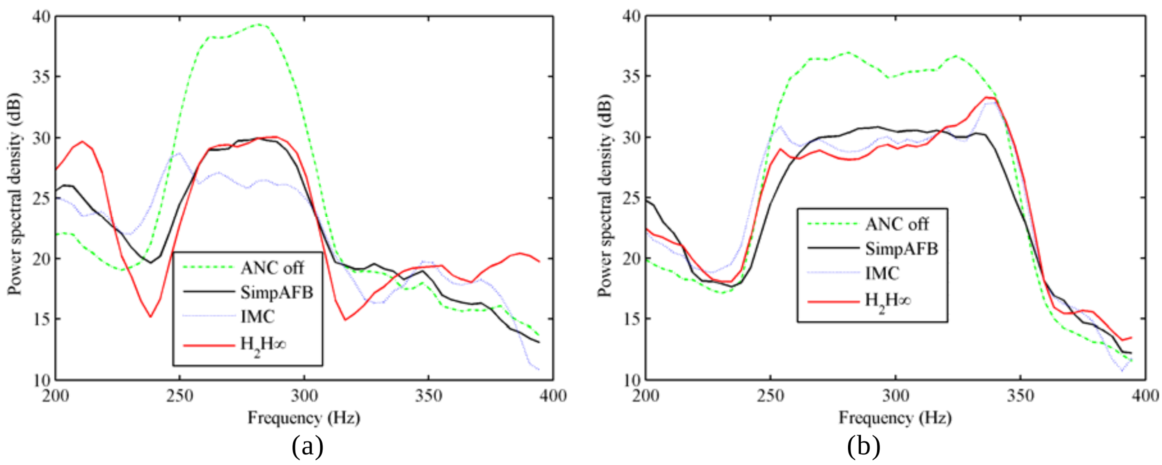


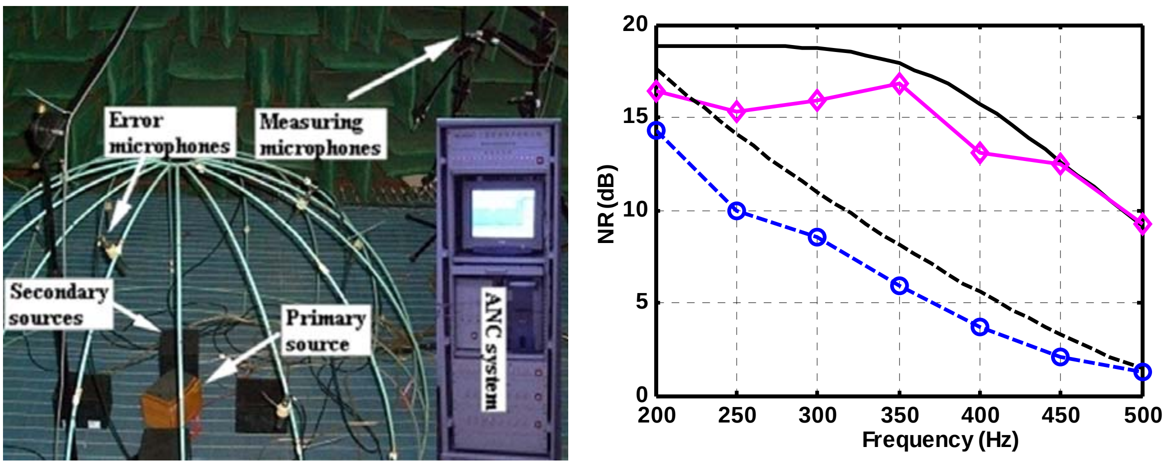
Figure 4 – Experimental results of different feedback ANC systems in a duct for narrow band noise: (a) 250–350 Hz and (b) 250–450 Hz.

Although there have been many novel, complex, and high-performance algorithms published in academic journals, robust, simple, and effective algorithms are preferred in practical applications.

2.3 Hardware and Systems

An ANC system normally consists of secondary sound sources, reference sensors, error sensors, and a controller, where the controller processes the signals from the sensors and drives the secondary sound sources to interact with the primary sound. The performance of an ANC system depends on a number of parameters, such as control source arrangement (number and location), the cost function to be minimized by the controller, error sensor arrangement (number and location), reference signal quality (only for feedforward control systems) and the electronic controller, in order of optimization for achieving the best performance [9]. The type of control source is also important. Figure 5 shows the noise reduction obtained by monopole control sources and compound control sources for a noise source radiation problem, where a compound control source is constituted by two matched loudspeakers (monopoles) with different gains and opposite phases [15]. It can be shown that the compound sources can be used to substitute the monopole sources to reduce the number of control channels or to improve the noise reduction performance of the ANC system.

Sometimes, reference sensors can be omitted in feedforward control systems to reduce the hardware cost and design complexity of the whole active control system. For example, the fundamental and harmonic frequencies of the transformer noise are characterized by even multiples of the line frequency and the variation of the fundamental frequency is usually no more than 0.5%, so it is a good situation for using an internally synthesized signal of preset frequencies as the reference signal. With this method, the system does not need an extra sensor to pick up the noise signal and avoids complex signal conditioning hardware for amplifying and filtering the small noisy signal. It also avoids an extra AD converter, which reduces the hardware cost of the system as well as increases the robustness of the system, owing to the use of a stable reference signal. Considering the digital additional delay and the secondary path delay, the time domain simulation and experimental results of the transformer algorithm with an internally synthesized reference signal are shown in Table 2 for the 100 Hz component with a frequency mismatch of 0.5% [17], where it is clear that the noise reduction can reach more than 25 dB.



(a) (b)

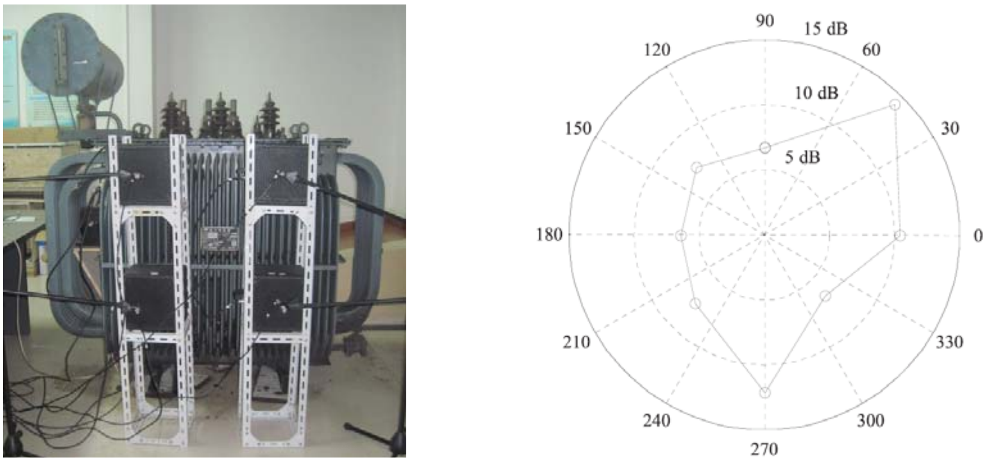
Figure 5 – ANC of noise radiation with monopole or compound secondary sources: (a) the experimental system; and (b) noise reduction of the system: experimental (blue circles) and numerical (black dashed line) data of the monopole secondary sources, and experimental (pink diamonds) and numerical (black solid line) data of the compound secondary sources.

Table 2 – Noise reduction of the transformer algorithm with an internally synthesized reference signal.

Secondary path distance (cm)	NR (dB) at 100 Hz		
	Total delay (samples)	Simulation	Experiment
20	6	31.6	29.5
57	9	30.9	28.3
113	14	29.9	26.2

Although centralized fully coupled multi-channel ANC systems can achieve optimal performance in terms of noise reduction, such systems are costly in terms of complexity, cabling, and sensitivity to individual failure as the channel number increases. An alternative strategy is to distribute the control over multiple local controllers, which has been shown to be effective in a number of cases. This has the potential for mass production of generic active control modules, including an actuator, sensor, and self-tuning controller. Figure 6 shows the experimental setup and performance of a decentralized multi-channel feedback analog control system [18].

The multi-channel system consists of four independent controllers arranged in a planar shape and equally separated at distances of 50 cm. Each independent single-channel controller is composed of an error microphone, an analog controller, a power amplifier, and a loudspeaker. The distance between the error microphone and the loudspeaker is 20 cm, and the controller is a four-order bandpass circuit designed with the H_∞ optimization technique. The independent single-channel controller is designed to produce than 15 dB of noise reduction around 100 Hz with less than 6 dB of noise amplification at other frequencies. It can be observed from Figure 6 that more than 6 dB of global noise reduction is achieved. Therefore, a decentralized multi-channel feedback analog control system might be able to provide a practical and economic solution for transformer noise control.



(a) (b)

Figure 6 – (a) The decentralized system beside a transformer with four independent feedback controllers arranged in a planar shape. (b) Noise reduction at 100 Hz of eight measurement points at 1.5 m high and 45° separated evenly around the midpoint of the decentralized system with a distance 2.5 m.

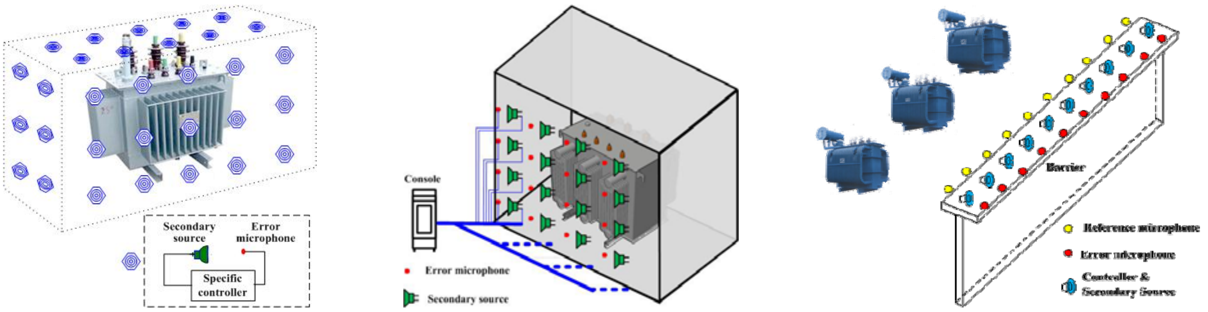
Some ANC applications require experimental verification before design and implementation in real products, where a general-purpose controller is often needed. The controller is actually an instrument for experimental study and concept validation with the following features: a multi-channel system embedded with many different algorithms; short delay so both feedforward and feedback architectures can be tried; large memory so the lengths of both control filters and filters for modeling the cancellation path can be set sufficiently long to check the performance limits of the ANC system; flexibilities such as centralized or decentralized control; and a front end for the user to choose tonal, narrow-band, or broadband control, as well as the specific band for the control [19]. The controller is often facilitated with fast floating-point digital signal processors or FPGA for real-time anti-sound filtering and general microcontrollers for general management, such as a graphical user interface, performance and system monitoring, and communication between different modules. After the experimental study, the relationships between system performance, architecture, control sources and sensors, hardware and algorithms are understood, and then a specific robust, low-cost ANC system can be designed to suit the application requirements.

3. APPLICATIONS OF ACTIVE NOISE CONTROL

3.1 Active Control of Transformer Noise

Although many efforts have been made on active control of transformer noise, successful applications are still rare. The main difficulties are the effectiveness, robustness, and cost of the ANC systems; that is, the lack of durable transducers and hardware, and the lack of robust adaptive algorithms. Because the noise around a transformer often contains more than low-frequency components, passive noise methods should generally be combined with active methods to provide a total solution. What the industry desires is easy installation, easy maintenance, and a low-cost system with reasonable noise reduction performance. Figure 7 shows three different ANC solutions that have been applied to different scenarios, such as outdoor transformers in free space, transformers in an enclosure with one opening, and outdoor transformers with existing barriers [19].

Figure 7(a) shows an outdoor transformer in free space, where tens or hundreds of loudspeakers are located around the transformer to reduce its total radiation. Both centralized and decentralized systems can be used, and feedforward algorithms can use an internally synthesized signal of preset frequencies as the reference signal [20]. In generally a greater than 10 dB global attenuation can be obtained at 100 Hz. The application scenario shown in Figure 7(b) is a transformer inside an enclosure with one side opened, where a planar virtual sound barrier is used to block sound radiation but without blocking air and light. Experimental results show that more than 15 dB for 100 Hz and 8 dB for 200 Hz can be obtained in the far field [21]. The benefits of this system are that the number of control channels can be reduced significantly and that the cost of the system is reduced, because the entire system can be placed indoors and requirements of waterproof sensors and control sources are relaxed. Active sound barriers can be used around transformers to reduce the required height of passive barriers or to increase the performance of the current barrier, as shown in Figure 7(c), where active control can introduce an additional insertion loss of around 4–6 dB in the far field in experiments [22].

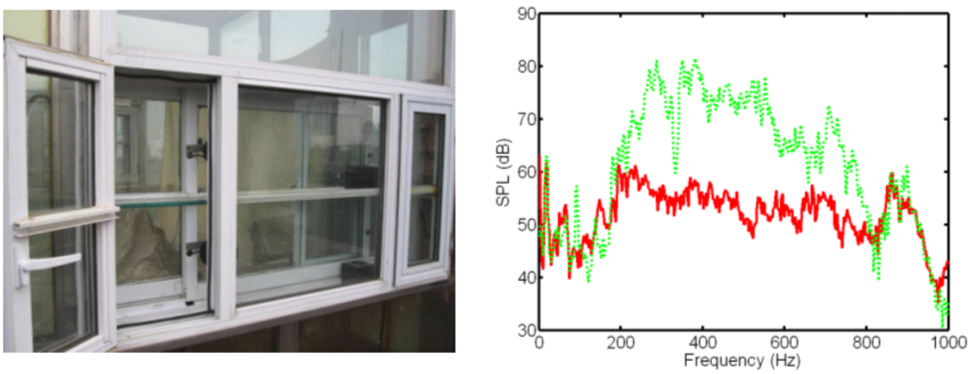


(a) (b) (c)

Figure 7 – Different ANC solutions to different transformer noise scenarios: (a) outdoor transformers in free space, (b) transformers in an enclosure with one opening, and (c) outdoor transformers with existing barriers.

3.2 Active Noise Control in Natural Ventilation Windows

Windows are typically the weakest link in sound insulation among all the components of a building façade, especially in the low-frequency range. Active control of sound transmission through single-glass or doubled-glazed windows has been investigated thoroughly, and the mechanisms of control and performance are now well understood. One typical natural ventilation window comprises two layers of glass staggered to create a natural ventilation path. ANC has been applied to such a window without incurring a large flow constraint on the airflow in the ventilation path [23]. Figure 8 shows a photo of such a window with ANC systems, as well as its noise reduction performance.



(a) (b)

Figure 8 – (a) A photo of a staggered-type natural ventilation window with ANC systems and (b) the noise reduction performance of the ANC system.

As shown in Figure 8(a), the prototype natural ventilation ANC window has been installed in a glass room with dimensions 2.0 m long, 2.5 m wide, and 2.5 m high. The window is 1.1 m wide and 0.6 m high, and is divided into left, middle, and right parts. The window consists of two layers of glass (outside and inside) with a spacing of 0.1 m. The middle window is divided into upper and lower parts, so that each part can be treated as a separate ventilation duct. By applying a single-channel feedforward ANC system in each duct, the low-frequency noise passing through the path can be cancelled almost completely to a background noise level, as shown in Figure 8(b). Measurements on-site show that the sound insulation performance of such natural ventilation ANC windows can achieve such a cancellation when the windows are closed [24].

3.3 Active Noise Control in a Communication Chassis

In a communication chassis, the operation of a cooling fan causes noise problems. Traditional methods cannot achieve satisfactory performance in a low-frequency range because of weight and volume constraints. ANC systems can be integrated into the cabinet to increase noise reduction performance of the whole system by reducing the low-frequency noise components. Figure 9 shows three types of implementation, (a) using an ANC system for an existing muffler, (b) mounting an active acoustic enclosure, and (c) mounting an active muffler. The application of ANC results in an additional overall noise reduction of 6–15 dB [25].

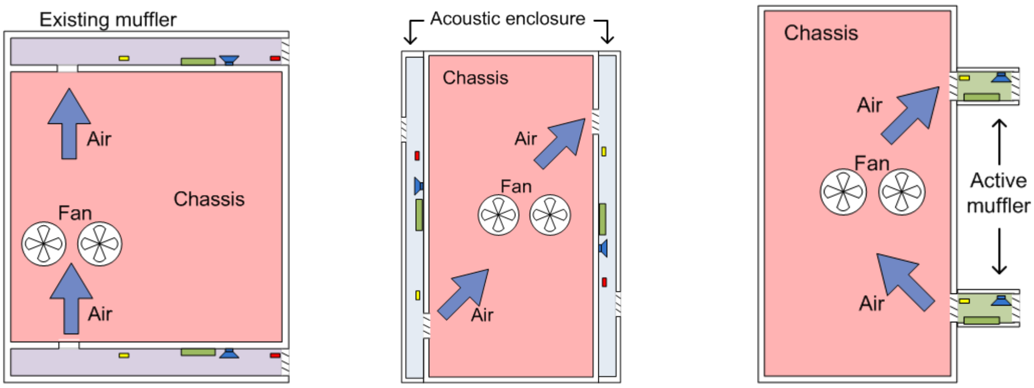


Figure 9 – ANC implementations in a communication chassis: (a) an ANC system for an existing muffler, (b) an active acoustic enclosure, and (c) an active muffler.

Owing to limitations of space, only three projects are described above. In fact, we have recently performed many other ANC projects, such as active control of large impulsive noise in headsets and ANC in the exhaust port of a vacuum cleaner, in a locomotive, of humming noise from haul trucks, and for indoor barriers in open-plan offices to increase speech privacy [26–30]. Unlike our previous research, all these projects are funded by industry bodies and their aims are not to perform academic research, but to develop commercial products. Because the objective of these projects is to implement ANC technologies in commercial products, the challenges are different from those previous research projects. In these implementation projects, marketing, production, and quality management, and robust, low-cost, easy installation and maintenance sometimes become more important.

4. CONCLUSIONS

Although the fundamental theories and methods of ANC have been established over the last few decades, wide application of the technology is only just beginning. With increasing numbers of companies investigating the applications of noise control in their products, increasing research and development projects will come from industry or will be performed by the industry. The applications of ANC are entering a golden age.

ACKNOWLEDGEMENTS

The first author, Xiaojun Qiu, would like to thank his former supervisor, Prof. Jiazheng Sha (1930–2014) of Nanjing University, who pioneered active control research in China and led him into the field. Xiaojun Qiu would also like to thank his mentor and friend, Prof. Colin Hansen in the University of Adelaide, who has helped him consistently in his research and applications of ANC all these years. All three authors would like to thank their team members at Nanjing University (Dr. Haishan Zou, Dr. Zhibin Lin, Dr. Jiancheng Tao, Dr. Kai Chen, Dr. Limin Zhang, Mr. Ningrong Li, and their students) for exploring the applications of ANC technology together over the last ten years.

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