FEATURED ARTICLE

Beyond Anti-Noise: Foundations and the Future of Active Sound Control

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Introduction

Active sound control has today been applied to many practical noise control challenges, with commercial applications including car engine and road noise control, propeller aircraft noise reduction and, of course, noise canceling headphones. Research and development into further utilization of the technology is also continuing in a variety of areas, notably including maritime applications, consumer goods, and the built environment. However, the historical pathway to this point of productivity has been long, with some interesting twists in the scientific understanding and in both the technology development and its uptake.

The active control of sound is based on the fundamental physical principle of how waves generated by two or more acoustic sources interfere to create a desired sound field distribution. The physical occurrence of interference between waves was established in the context of light by Young (1804), and we have probably all experienced the associated double-slit experiment (tinyurl.com/4zx3nfwt). This understanding was extended to sound waves by Lord Rayleigh (Strutt, 1878), who reported observing "places of silence" in the sound field generated by two electromagnetically excited tuning forks. Lord Rayleigh, however, repeatedly noted the practical challenges of realizing such interference patterns experimentally due to the need to carefully synchronize the multiple sources. This partially explains why almost a century passed before active sound control systems, which rely on carefully tuned destructive and constructive sound field interference to achieve various objectives ranging from spatial audio reproduction to acoustic cloaking (Cheer, 2016), became practically viable.

This article provides a brief tutorial on the physical basis of active sound control before providing a review of its historical development and key milestones. Finally, future potentials of active sound control that may have an influence on our everyday lives are discussed.

Physical Fundamentals of Active Sound Control

The fundamental basis for active sound control techniques is based on the superposition principle, which is a fundamental property of linear systems, that states that when two or more waves travel through the same space at the same time, the net response is the sum of the individual waves. Many everyday situations involving acoustics can be well approximated as linear systems and, therefore, follow the principle of superposition. For example, in your classic hi-fi stereo setup that uses two loudspeakers, the sound that we hear is given by the sum or superposition of the two pressures generated by each loudspeaker at each ear. In acoustics, sound pressure is measured relative to the stationary ambient pressure. This means that pressures that are larger than the ambient pressure correspond to positive sound pressures and pressures that are smaller than the ambient pressure correspond to negative sound pressures. Consequently, considering the stereo hi-fi application, two positive pressures produced at our ear would be superimposed to give an enhanced total sound pressure, whereas a positive pressure superimposed with a negative pressure would give a reduction in the total sound pressure level.

The concept of superposition is illustrated in **Figure 1**, where examples of the superposition for two sinusoidal signals are shown. **Figure 1**, *top*, is widely used to illustrate the principle of active noise control. It shows two sinusoidal signals with equal amplitude but opposite phase. Superimposing these two signals results in the primary signal being exactly canceled by the secondary signal, leading to a combined signal with a value of zero.

https://doi.org/10.1121/AT.2024.20.2.31

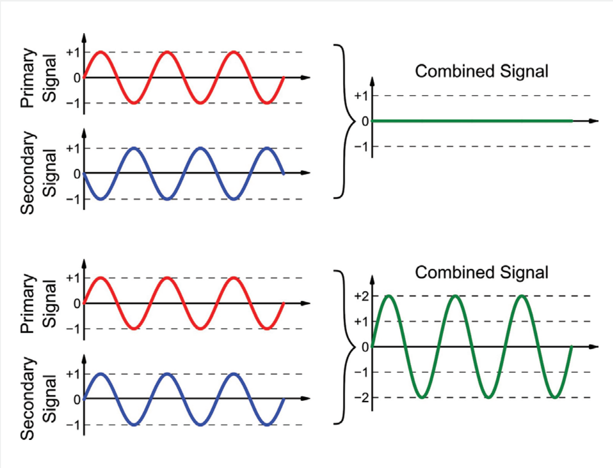


Figure 1. *Illustration of two basic superposition effects using sinusoidal wave signals.* ***Top:*** *sound cancellation using destructive interference.* ***Bottom:*** *sound enhancement using constructive interference.*

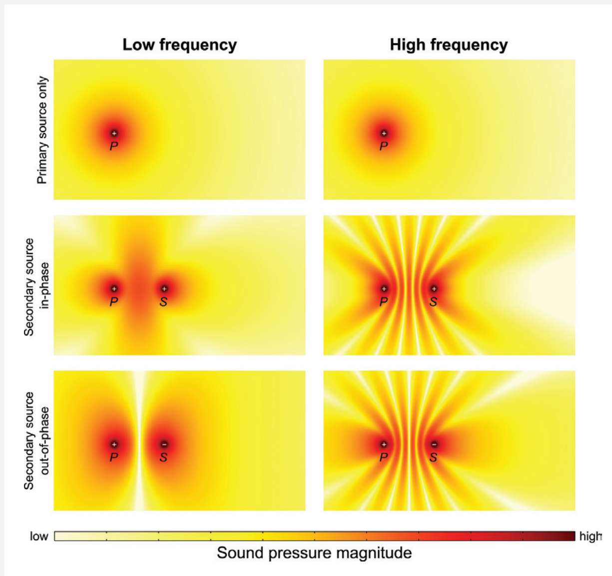
This process is commonly called "noise cancellation" and the term "anti-noise" is used to describe the secondary sound signal as being the "opposite" of the primary signal, although this perspective misses many details of practical active noise control system design. It is worth noting that this concept is not limited to sinusoidal signals but can, in principle, be extended to arbitrary primary signals (e.g., speech) as long as the secondary signal can be generated to exactly cancel the primary signal.

Figure 1, *bottom*, illustrates another fundamental consequence of the superposition principle, which is less often discussed in the context of active noise control but is relevant more broadly to active sound control. In this case, the two sinusoidal signals are in phase with each other, which results in constructive interference between the two signals and a doubling in the amplitude of the combined signal. This principle is utilized in various active sound control applications, including active sound equalization (Kuo and Ji, 1995), where active control may be used not only to attenuate unwanted noise but also to enhance wanted noise. For example, these techniques can be used to actively modify the acoustic characteristics of an internal combustion engine to make a low-power engine sound sportier (Samarasinghe et al., 2016).

The examples shown in **Figure 1** apply to interference mechanisms in both time and space. Thus, in active sound control, it is crucial to control the secondary signal both temporally and spatially. This means that actively controlling sound throughout a large volume of space becomes challenging.

Figure 2 illustrates this challenge for a spherical sound wave radiated by a monopole source (e.g., a loudspeaker) into free space. **Figure 2**, *top*, shows slices through the sound pressure field radiated by the primary source (P) at two different frequencies, with *dark red* corresponding to higher pressure amplitudes and *light yellow* representing lower sound pressure levels. In **Figure 2**, *middle*, a secondary source (S) has been added at a distance away from the primary source and is driven in phase with the primary source. This results in a complex interference pattern, with areas of low sound pressure level due to destructive interference and areas of enhanced sound pressure level due to constructive interference. As the frequency is increased and the wavelength becomes smaller, the complexity of the interference pattern also increases,

Figure 2. *Sound pressure radiated by a primary source (P) and a secondary source (S), modeled as monopole sources, into a three-dimensional free field at low and high frequency. The spacing between the sources equates to 0.7 of the acoustic wavelength at low frequencies and 3.5 times the acoustic wavelength at high frequencies.* ***Top:*** *the field is radiated by the primary source only.* ***Middle:*** *the secondary sound source radiates sound in phase with the primary source.* ***Bottom:*** *the secondary sound source is out of phase with the primary source.*



with more areas of both low and high sound pressure levels being produced.

These sound field interference patterns highlight two crucial challenges for active sound control in three-dimensional sound fields: First, the phase of the sound field radiated by a single secondary source cannot be controlled independently at different locations in space. This means that driving the secondary source with an out-of-phase signal to achieve cancellation at one location can lead to (possibly unwanted) sound enhancement at another location. Second, because the interference pattern depends on the frequency, a quiet zone at one frequency may correspond to a region of enhanced sound pressure level at another frequency, which complicates the tuning of the secondary source.

A common misconception in terms of active noise control is that to "cancel" sound, the secondary sound source needs to be driven out of phase with the primary source. This scenario is illustrated in **Figure 2**, *bottom*, which shows that when the primary and secondary sources are not collocated at the same point in space, cancellation throughout the space does not result from driving the two sources out of phase with each other. In fact, driving the secondary source out of phase simply leads to regions of cancellation and enhancement swapping positions compared with the case when the sources are in phase with each other.

In practical active sound control systems, the secondary source needs to be driven such that the desired pressure reduction or enhancement occurs at the required target location. In many practical cases, the primary source does not act at a point but is distributed over space and a single secondary source simply cannot generate the complex sound field required, especially in large volumes (such as rooms or aircraft cabins) and at higher frequencies. As a result, multiple secondary sources are used in practice to achieve the required degree of sound control over a wider spatial volume.

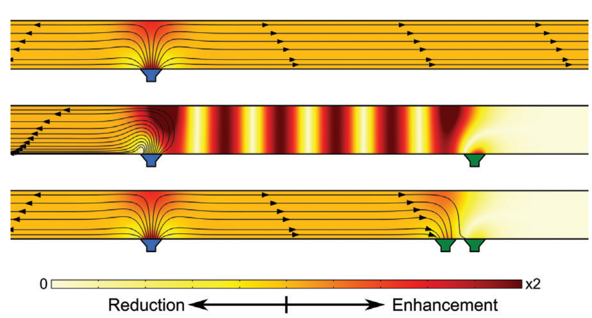
We now know that to actively control the sound radiated by a primary source, we need at least one secondary sound source that must be driven with a certain phase relationship with respect to the primary source to achieve the desired sound field. In the context of active noise control, this often raises the question about the energy balance in the system:

> "If a secondary sound source is introduced to reduce the sound pressure but this secondary sound source also introduces energy into the system via its radiated sound power, why is the total energy in the system not increased by the secondary source?"

To provide insight into this interesting question, **Figure 3** shows the pressure magnitude (*colormap*) and sound energy flow or acoustic intensity (*black streamlines*) for two different approaches to realizing active noise control in a duct. The first system (**Figure 3**, *top*) represents the duct with only the primary source radiating sound. The resulting pressure magnitude field in the duct is mostly uniform, indicating the propagation of plane waves (the pressure magnitude varies moderately in the vicinity of the primary source, which is a result of the near field). The sound energy flows along the duct in both directions away from the primary source, as one might intuitively expect.

In the second system (**Figure 3**, *middle*), a secondary sound source is introduced some distance away from the primary source. The secondary source is driven to achieve destructive interference and therefore noise cancellation to the right of the secondary source. The near-zero pressure magnitude field on the right of the secondary source clearly shows that this is achieved.

Figure 3. *The sound pressure magnitude (**colormap**) and steady-state flow of acoustic energy (**black streamlines and arrows**) in a duct due to a single primary source (**top**), active sound control using a single secondary source (**middle**), and active sound control using a pair of secondary sources (**bottom**).*



However, a specific pressure field pattern can be observed between the primary and secondary sound sources, which corresponds to the formation of a standing wave. The *colormap* in this region reveals that the pressure is doubled in certain places where the primary and secondary sound fields interfere constructively. This shows that even though it is possible to reduce the sound pressure in certain regions of the duct with a single secondary sound source, the pressure is increased at other locations. In terms of the energy flow, the streamlines in **Figure 3** indicate that the sound energy only travels to the left, with the standing wave field effectively operating as a barrier through which the sound radiated by the primary source cannot propagate. In this case, therefore, the energy is not reduced but is simply reflected by the action of the secondary source as if it were a rigid barrier.

To achieve full sound cancellation in the right half of the duct without introducing either a standing wave field or regions of increased sound pressure, it is necessary to introduce an additional secondary source as shown by the final system (**Figure 3**, *bottom*). The original secondary source is now driven to cancel the sound waves generated by both the primary and additional secondary sources to the right of the secondary sources. The additional secondary sound source is driven to cancel the sound radiated by the original secondary source to the left of the secondary sources. In this case, the pressure field to the right of the secondary sound sources is fully canceled, whereas the pressure field between the primary and secondary sound sources is now unchanged by control. The total acoustic energy in this system is clearly reduced, but where does the energy go? The streamlines reveal that the acoustic energy radiated by the primary source propagates away from the source in both directions, but the energy propagating toward the secondary sources then flows into the first secondary source and does not propagate further along the duct. This control strategy is typically called active absorption control because the secondary source absorbs the acoustic energy. The mechanism by which the energy is absorbed depends on the nature of the secondary source.

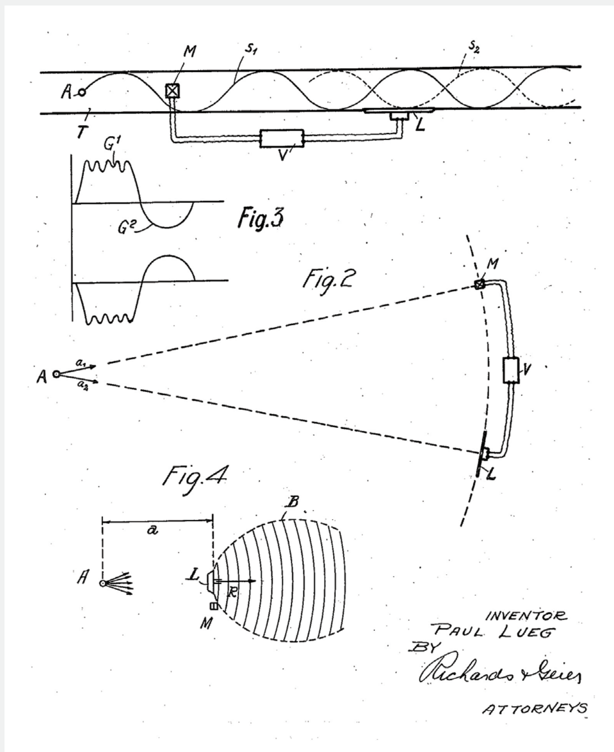
The physical fundamentals of active sound control discussed here briefly can be extended to more complex scenarios where it is necessary to bring together an understanding of the physical acoustics, the signal processing, and the control theory. The interested reader is referred to the many excellent textbooks on the subject including Nelson and Elliott (1991).

Historical Development and Milestones

Ideation

The invention of active noise control is often attributed to Lueg (1933), who filed a patent application in Germany (and subsequently in the United States [1934]) covering the concept of controlling noise in both one-dimensional and three-dimensional environments via destructive interference. However, a French patent, filed a matter of weeks previously by Coanda (1932), initially proposed the idea. The story behind Lueg and his seminal patent

Figure 4. *Diagrams from an early active noise control patent. M, a microphone; L, a loudspeaker; V, an electronic controller; A, the acoustic primary source. The* ***top*** *figure shows a potential duct active noise control realization. T, the duct; S_1 the primary sound wave; S_2, the secondary source wave. Fig. 2 shows a potential system for the control of spherical waves in a free-field environment. Fig. 3 depicts the meaning of phase opposition for nonsinusoidal signals, shown by the irregular curves G_1 and G_2. Fig. 4 shows an alternative free-field implementation where the secondary source is at a distance (a) from the primary source and where B is the zone of noise reduction that primarily occurs in direction R. Reproduced from Lueg (1934).*



has been nicely discussed in *The Journal of the Acoustical Society of America* by Guicking (1990) and the common mix-up in attribution of the invention is highlighted in a following comment by de Heering (1993).

Despite this interesting historical note, it is quite widely accepted that Lueg's patent (1933) provides the cornerstone of active noise control, with the diagrams page from the patent (Lueg, 1934) reproduced in **Figure 4**, proposing the first physically realizable mechanisms of achieving noise control via wave interference. In the top figure shown in **Figure 4**, Lueg proposes a means of achieving noise control in the duct application shown in **Figure 3** to introduce the physical basis of active noise control. This practical realization utilizes a microphone (M) to detect the unwanted primary wave (S_1) which is then manipulated by an electronic controller (V) and used to drive the loudspeaker (L), which generates the secondary wave, (S_2) that has equal amplitude and opposite phase to the primary wave (S_1). The two acoustic waves will thus interfere destructively and lead to a reduction in the noise level, as discussed in relation to **Figure 1**. In addition to the one-dimensional duct application, Lueg also presented concepts for the control of free-field sound in three-dimensional spaces ("Fig. 2" and "Fig. 4") and considered the control of sound waves that are nonsinusoidal in "Fig. 3."

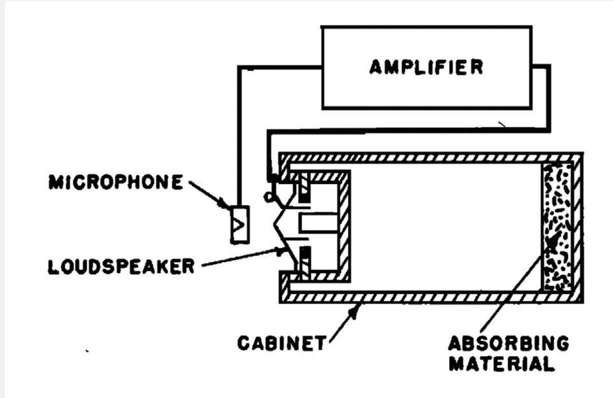


Figure 5. *The "electronic sound absorber" proposed by Olson and May (1953) in which a microphone signal is used to drive a loudspeaker after modification by an amplifier. The loudspeaker is enclosed in a cabinet with enclosed absorbing material. Reproduced from Olson and May (1953), with permission from the Acoustical Society of America.*

Olson's Electronic Sound Absorber

Despite the clarity and insight provided by Lueg's patent (1933), a practical system was not demonstrated for another two decades due to limitations in the available electronic hardware at the time. A significant step forward, however, came via the work of Olson and May (1953), which demonstrated a practical method for realizing an active noise control system. The proposed system shown in **Figure 5,** like the conceptual systems in Lueg's patent (1933), utilized a microphone, amplifier, and loudspeaker. However, in the case of Olson and May's work (1953), the control system was based around tuning the feedback between the microphone and loudspeaker to generate a zone of noise cancellation around the microphone rather than achieving control via a feedforward approach using the prior knowledge of the unwanted primary noise provided by the "upstream" microphone in the duct system shown in **Figure 4**. In addition to the first practical demonstration of active noise control, perhaps the more impressive contribution from Olson and May (1953) was their foresight in the breadth of potential active noise control applications. A summary of the diagrams depicting potential applications is presented in **Figure 6.**

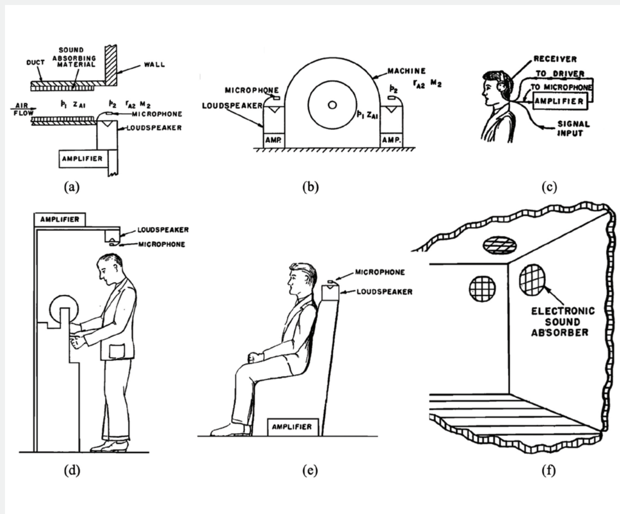


Figure 6. *A summary of the potential active noise control applications proposed by Olson and May (1953) and Olson (1956). Applications include control of noise radiation from ducts (**a**) and machinery (**b**); noise canceling headphones (**c**); active reduction of noise around the head of a machinery operator (**d**) or the occupant of a seat in an aircraft or automobile (**e**); and active control of the acoustic environment in a room (**f**). Reproduced from Olson and May (1953) and Olson (1956), with permission from the Acoustical Society of America.*

Fighting Noise with Noise

At a similar time to when Olson and May (1953) proposed their feedback active noise control system, Conover (1956) proposed a practical feedforward active noise control system for the reduction in the harmonic noise radiated by electrical mains power transformers (**Figure 7**). This system provided noise reduction in the order of 15 dB, but the performance was significantly degraded by changes in the transformer noise over time due to operational conditions and therefore required regular adjustment by the operator of the amplitude and phase to maintain control. Although Conover (1956) discusses a potential mechanism of automatically adjusting the control system, he notes that "development of an inexpensive system of this type would be quite a project," and this technological limitation largely stalled the development of active noise control systems once more.

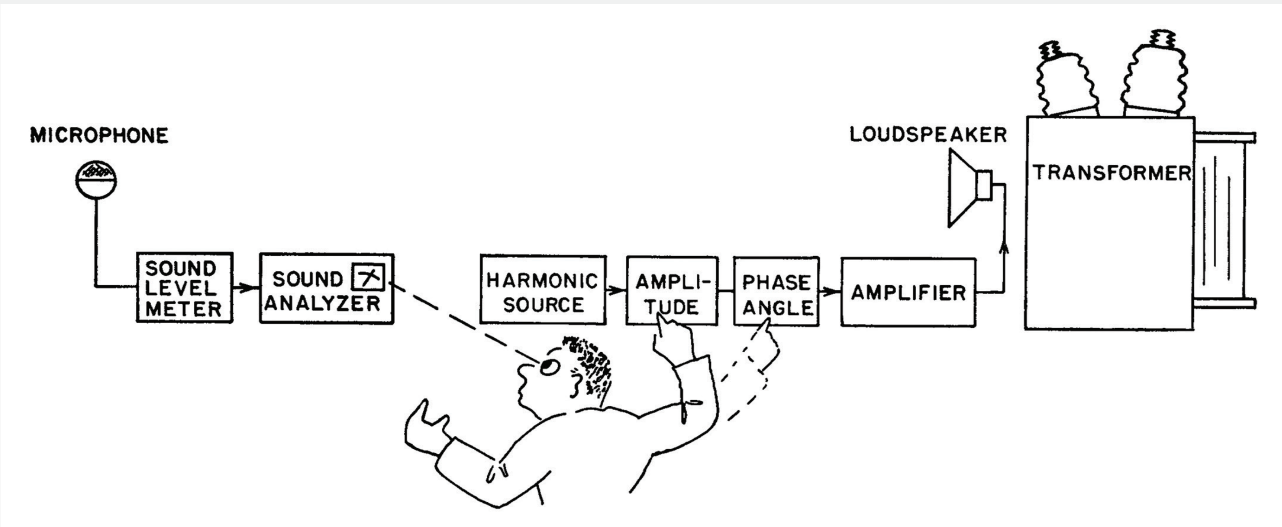
Advent of Digital Systems

The ability to automatically adjust the magnitude and phase in a tonal active noise control system became a practical reality with the emergence of digital signal-processing methods and systems in the 1970s. The first digital active noise control systems were reported in the work by Kido (1975) and Chaplin et al. (1978), the latter of whom proposed a digital waveform synthesizer to adaptively control the noise generated by the repetitive processes typical of many machinery noise problems. These early works spawned modern digital feedforward active control system design and, correspondingly, the number of academic publications has grown rapidly since this foundational work.

Despite the importance of this early work on the realization of digital active noise control systems, the most significant step forward came with the proposal of the Filtered-x Least-Mean-Square (FxLMS) algorithm for active noise control applications (Burgess, 1981) and its generalization to the minimization of multiple microphone signals (Elliott et al., 1987). This algorithm can effectively handle the real-world variations over time that require changes in the amplitude and phase of the control signals, as reported by Conover (1956) and referenced in **Figure 7**.

The FxLMS algorithm was derived from the adaptive noise canceler developed for the removal of additive noise from electrical signals (Widrow et al., 1975) but takes into account the phase shift due to the response between the secondary source and the microphone that, if ignored, would lead to an unstable system. The FxLMS algorithm has been widely studied and the interested reader is referred to Kuo and Morgan (1996) and Elliott

Figure 7. *Active noise control system for transformer noise reduction. The system uses a microphone and analysis system that the user monitors to manually adjust the amplitude and phase of a harmonic signal, with the same frequency as the transformer harmonic being controlled, which is then used to drive a loudspeaker. Reproduced from Conover (1956), with permission from the Acoustical Society of America.*



(2001) for a more complete introduction to the algorithm. Suffice it to say, however, despite the emergence of many other adaptive active noise control algorithms, the FxLMS algorithm has remained the most widely applied due to its robustness to real-world challenges and relative simplicity.

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Application and Exploitation

The advent of digital signal processing was the key technology trigger that enabled researchers to seriously explore the potential application of active noise control to real-world challenges. This resulted in a rapid growth in research, which was reflected by a sharp increase in published articles from around the late 1980s. Early application examples include engine noise in cars (Elliott et al., 1988), propeller aircraft noise (Elliott et al., 1990), rotor tone noise in helicopters (Boucher et al., 1996), road noise in cars (Sutton et al., 1994), and the exploration of noise canceling headsets particularly for pilot and military applications (Goodfellow, 1994). This period of active noise control research was extremely productive, providing advances in the areas of physical acoustics, signal processing and control and, significantly, understanding of how these various aspects of active noise control systems interact.

Despite the promise and many impressive practical demonstrations of active noise control systems in the late 1980s and early 1990s, widespread commercialization of the technology was not achieved. As noted at around that time by Elliott and Nelson (1993), this can perhaps be related to the technology being "somewhat oversold," with the result of a prevailing expectation that active noise control would be able to silence all noise problems.

Following the technology trigger associated with the availability of digital systems, the boom in research in the late 1980s and early 1990s coincided with a peak of inflated expectations. With inflated expectations, it is perhaps unsurprising that a period of disillusionment in the technology followed, with the technology not delivering what was perhaps misleadingly promised. However, active noise control technologies emerged from this period with active noise canceling headphones, as envisioned by Olson (1956) and shown in **Figure 6c**, moving from a high-cost industrial technology to a consumer product in 2000 (see tinyurl.com/2p96rfpe) and large-scale noise control systems being commercialized in passenger propeller aircraft by Ultra Electronics (Hinchliffe et al., 2002). Versions of these successful products are still in operation today, and by demonstrating the value of active noise control technologies when integrated effectively and applied to well-suited noise control challenges, they moved the technology into a period of enlightenment.

Once useful, functional, and cost-effective applications of active noise control began to emerge, with appropriate levels of expectation, the route for applications opened in a variety of areas. For example, in the automotive sector, although early systems demonstrated the feasibility of both engine and road noise control, excluding early production vehicle systems such as that installed briefly in the Nissan Bluebird (Hasegawa et al., 1992), utilization of active engine noise control only began to grow in the early 2000s (Sano et al., 2001) and became widespread around a decade later. Many automotive manufacturers now utilize active engine noise control, particularly in hybrid vehicles or vehicles with cylinder deactivation technology where active control enables a more consistent driving experience (Samarasinghe et al., 2016).

Although active engine noise control has now been in a period of productivity for some time, many other applications of active noise control stalled or have yet to reach this point. For example, active control of road noise has not yet quite reached this stage due to its more challenging nature. Some production vehicles with road noise control have been released, with the first production vehicles launched in 2020 by Hyundai using a Harman control system (see tinyurl.com/2swv2tk6) and by Land Rover using a Silentium system (see tinyurl.com/tz4k66e8). However, usage has yet to become mainstream. This may, however, change quite rapidly with the increasing market share taken by electric vehicles, whose acoustic environment is more strongly dominated by road noise.

Future Potentials

Many more applications of active sound control exist than can be discussed in this article, including in the marine sector (Daley et al., 2004) and built environment (Lam et al., 2021), with a spectrum of levels of technology maturation. It is interesting to note that like many technologies, active control has taken its time to reach widespread use. This was initially due to a lack of suitable supporting technology but then became a challenge of aligning expectations to realistic and often physically imposed performance limitations. The future of active control is certainly now generally within a period of productivity, with clear understanding of what can physically be achieved with active treatments. Applications are now typically focused appropriately and rather than utilizing active control as an add-on solution to fix a problem, it is increasingly being treated as part of an integrated design process with passive noise control treatments.

Due to a wider understanding and reducing costs, active sound control is increasingly being explored for more cost-sensitive applications, such as consumer goods including washing machines and dishwashers (Mazur et al., 2019). Additionally, with the explosion of interest and research into artificial intelligence, there is a growing collection of novel active sound control-based systems that provide new functionality, including situation-dependent behavior or a personalized experience.

Acknowledgments

Jordan Cheer's time to prepare this article was supported by the Intelligent Structures for Low Noise Environments (ISLNE) EPSRC Prosperity Partnership (EP/S03661X/1). Thanks to Steve Elliott for his helpful comments on a draft of this article.

References

Boucher, C. C., Elliott, S. J., and Baek, K. H. (1996). Active control of helicopter rotor tones. *Proceedings of Inter-Noise 96, International Congress on Noise Control Engineering,* Liverpool, UK, July 30 to August 2, 1996, pp. 1179-1182.

Burgess, J. C. (1981). Active adaptive sound control in a duct: A computer simulation. *The Journal of the Acoustical Society of America* 70(3), 715-726. https://doi.org/10.1121/1.386908.

Chaplin, G. B. B., and Smith, R. A. (1978). The sound of silence. *Engineering* 218, 672-673.

Cheer, J. (2016). Active control of scattered acoustic fields: Cancellation, reproduction and cloaking. *The Journal of the Acoustical Society of America* 140(3), 1502-1512. https://doi.org/10.1121/1.4962284.

Coanda, H. (1932) *Procédé et dispositif de protection contre des bruits*. French Patent No. 762121, December 1932.

Conover, W. B. (1956). Fighting noise with noise. *Noise Control* 2(2), 78-92. https://doi.org/10.1121/1.2369194.

Daley, S., Johnson, F. A., Pearson, J. B., and Dixon, R. (2004). Active vibration control for marine applications. *Control Engineering Practice* 12(4), 465-474. https://doi.org/10.1016/S0967-0661(03)00135-7.

de Heering, P. (1993). Comments on "On the invention of active noise control by Paul Lueg" [J. Acoust. Soc. Am. 87, 2251-2254 (1990)]. *The Journal of the Acoustical Society of America* 93(5), 2989. https://doi.org/10.1121/1.405819.

Elliott, S. J. (2001). *Signal Processing for Active Control*. Academic Press, London, UK.

Elliott, S. J., and Nelson, P. A. (1993). Active noise control. *IEEE Signal Processing Magazine* 10(4), 12-35. https://doi.org/10.1109/79.248551.

Elliott, S. J., Nelson, P. A., Stothers, I. M., and Boucher, C. C. (1990). In-flight experiments on the active control of propeller-induced cabin noise. *Journal of Sound and Vibration* 140(2), 219-238. https://doi.org/10.1016/0022-460X(90)90525-5.

Elliott, S. J., Stothers, I. M., and Nelson, P. (1987). A multiple error LMS algorithm and its application to the active control of sound and vibration. *IEEE Transactions on Acoustics, Speech, and Signal Processing 35(10), 1423-1434.*

Elliott, S. J., Stothers, I. M., Nelson, P. A., McDonald, A. M., and Saunders, T. (1988). The active control of engine noise inside cars. *Proceedings* of *Inter-Noise 1988, International Conference on Noise Control Engineering,* Avignon, France, August 30 to September 1, 1988, pp. 987-990.

Goodfellow, E. A. (1994). A prototype active noise reduction in-ear hearing protector. *Applied Acoustics* 42(4), 299-312. https://doi.org/10.1016/0003-682X(94)90099-X.

Guicking, D. (1990). On the invention of active noise control by Paul Lueg. *The Journal of the Acoustical Society of America* 87(5), 2251-2254. https://doi.org/10.1121/1.399195.

Hasegawa, S., Tabata, T., and Kinoshita, T. (1992). *The Development of an Active Noise Control System for Automobiles*. Technical Paper 922086, Society Automotive Engineering, Warrendale, PA. https://doi.org/10.4271/922086.

Hinchliffe, R., Scott, I., Purver, M., and Stothers, I. (2002). Tonal active control in production on a large turbo-prop aircraft, *Proceedings of ACTIVE2002*, The 2002 International Symposium on Active Control of Sound and Vibration, Southampton, UK, July 15-17, 2002, pp. 369-378.

Kido, K. (1975). Reduction of noise by use of additional sound sources. *Proceedings of Inter-Noise 1975, The International Conference on Noise Control Engineering*, Sendai, Japan, August 27-29, 1975, pp. 647-650.

Kuo, S. M., and Ji, M. J. (1995). Development and analysis of an adaptive noise equalizer. *IEEE Transactions on Speech and Audio Processing* 3(3), 217-222. https://doi.org/10.1109/89.388150.

Kuo, S. M., and Morgan, D. R. (1996). *Active Noise Control Systems,* vol. 4. Wiley, New York, NY.

Lam, B., Gan, W. S., Shi, D., Nishimura, M., and Elliott, S. (2021). Ten questions concerning active noise control in the built environment. *Building and Environment* 200, 107928. https://doi.org/10.1016/j.buildenv.2021.107928.

Lueg, P. (1933), *Verfahren zur Dämpfung von Schallschwingungen*. German Patent No. 655508, January 1933.

Lueg, P. (1934). *Process of Silencing Sound Ocillations*. US Patent No. 2,043,416, March 1934.

Mazur, K., Wrona, S., and Pawelczyk, M. (2019). Active noise control for a washing machine. *Applied Acoustics* 146, 89-95. https://doi.org/10.1016/j.apacoust.2018.11.010.

Nelson, P. A., and Elliott, S. J. (1991). *Active Control of Sound*. Academic Press, London, UK.

Olson, H. F. (1956). Electronic control of noise, vibration, and reverberation. *The Journal of the Acoustical Society of America* 28(5), 966-972. https://doi.org/10.1121/1.1908532.

Olson, H. F., and May, E. G. (1953). Electronic sound absorber. *The Journal of the Acoustical Society of America* 25(6), 1130-1136. https://doi.org/10.1121/1.1907249.

Samarasinghe, P. N., Zhang, W., and Abhayapala, T. D. (2016). Recent advances in active noise control inside automobile cabins: Toward quieter cars. *IEEE Signal Processing Magazine* 33(6), 61-73. https://doi.org/10.1109/MSP.2016.2601942.

Sano, H., Inoue, T., Takahashi, A., Terai, K., and Nakamura, Y. (2001). Active control system for low-frequency road noise combined with an audio system. *IEEE Transactions on Speech and Audio Processing* 9(7), 755-763. https://doi.org/10.1109/89.952494.

Strutt, J. W. (Lord Rayleigh). (1878). *The Theory of Sound,* vol. 2. Macmillan, Cambridge, UK.

Sutton, T. J., Elliott, S. J., McDonald, A. M., and Saunders, T. J. (1994). Active control of road noise inside vehicles. *Noise Control Engineering Journal* 42(4), 137-147. https://doi.org/10.3397/1.2828351.

Widrow, B., Glover, J. R., McCool, J. M., Kaunitz, J., Williams, C. S., Hearn, R. H., Zeidler, J. R., Dong, J. E., and Goodlin, R. C. (1975). Adaptive noise cancelling: Principles and applications. *Proceedings of the IEEE* 63(12), 1692-1716. https://doi.org/10.1109/PROC.1975.10036.

Young, T. (1804). The *Bakerian* Lecture. Experiments and calculations relative to physical optics. *Philosophical Transactions of the Royal Society of London* 94, 1-16. http://doi.org/10.1098/rstl.1804.0001.

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