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ACTIVE NOISE CONTROL: A REVIEW OF THE FIELD

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Active noise control (ANC) is the application of the principle of the superposition of waves to noise attenuation problems. Much progress has been made toward applying ANC to narrow-band, low-frequency noise in confined spaces. During this same period, the application of ANC to broad-band noise or noise in three-dimensional spaces has seen little progress because of the recent quantification of serious physical limitations, most importantly, noncausality, stability, spatial mismatch, and the infinite gain controller requirement. ANC employs superposition to induce destructive interference to affect the attenuation of noise. ANC was believed to utilize the mechanism of phase cancellation to achieve the desired attenuation. However, current literature points to other mechanisms that may be operating in ANC. Categories of ANC are one-dimensional field and duct noise, enclosed spaces and interior noise, noise in three-dimensional spaces, and personal hearing protection. Development of active noise control stems from potential advantages in cost, size, and effectiveness. There are two approaches to ANC. In the first, the original sound is processed and injected back into the sound field in antiphase. The second approach is to synthesize a cancelling waveform. ANC of turbulent flow in pipes and ducts is the largest area in the field. Much work into the actual mechanism involved and the causal versus noncausal aspects of system controllers has been done. Fan and propeller noise can be divided into two categories: noise generated directly as the blade passing tones and noise generated as a result of blade tip turbulence inducing vibration in structures. Three-dimensional spaces present a noise environment where physical limitations are magnified and the infinite gain controller requirement is confronted. Personal hearing protection has been shown to be best suited to the control of periodic, low-frequency noise.

Active noise control (ANC) is the application of the physical principle of the superposition of harmonic waves to noise attenuation problems. Although first proposed over 50 yr ago, the field attracted little interest until the 1980s. Since the mid-1980s, much progress has been made toward applying ANC to narrow-band, low-frequency noise in confined spaces. During this same period, the application of ANC to broad-band or high-frequency noise, or noise in three-dimensional (3-D) spaces, has seen very little progress because of the recent quantification of serious physical limitations. The most important of these are noncausality, stability, spatial mismatch, and the infinite gain controller requirement. A brief historical perspective and a detailed review of the state of the art in active noise control will be presented in this paper.

HISTORICAL, GENERAL, AND THEORETICAL INFORMATION

ANC employs the principle of the superposition of waves to induce destructive interference to affect the attenuation of offensive noise. Simply put, this is the introduction of a wave of equal amplitude and frequency to the wave to be attenuated, but 180° out of phase. This process was believed to utilize the physical mechanism of phase cancellation to achieve the desired attenuation. However, this paper reviews current literature pointing to mechanisms other than phase cancellation that may be operating in the application of ANC.

ANC was first proposed by Paul Lueg in his 1936 patent "Process of Silencing Sound Oscillations."[1] This was one of the early applications of electronics, and although the system did not work in actual application, Lueg correctly understood the basic premise that, in theory, makes ANC attractive.

> The speed of sound in air is very much less than the speed of electrical impulses. This means that while a relatively slow sound wave is moving from a location where it is detected to a location where it can be attenuated, there is ample time available within the electronic circuit for signal processing and activation of control elements, to a greater or lesser degree, depending on the frequency range, type of noise, and physical extent of the system.[1]

It is worthwhile to look at the worldwide publication rate, averaged over 10 yr, to gain insight into the growth of the field. The 1950s yielded 3 papers per year, increasing to 15 papers per year in the 1960s. The 1970s and 1980s saw the field grow substantially with publication rates of 60 and 120 papers per year, respectively.[2] How research has been concentrated during this growth can be illustrated by examining keywords describing ANC areas, based again on numbers of papers: 57% theory, 30% experiment, 22% model computation, 7% model experiment,

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55% feedback control, 18% optimization, 16% control theory, 14% digital control, 19% adaptive systems, 26% 3-D control, 2% 2-D control, 44% 1-D control, 31% duct noise, 8% exhaust noise, 18% monopole sources, 15% dipole sources, 7% tripole sources, and 21% stability.(2) The ANC field now contains about 2000 researchers.

Generally, ANC can be broken down into four main categories: (1) one-dimensional field and duct noise; (2) enclosed spaces and interior noise; (3) noise in three-dimensional spaces; and (4) personal hearing protection.

Some specific applications of ANC are aircraft noise, noise in ducts and pipes, fan noise, and helicopter rotor noise. Additionally, work has been done in the areas of electrical transformer noise, intake and exhaust noise, and a wide variety of others.(3) The rapid development of active noise control stems from ANC's potential advantages in cost, size, volume, weight, and effectiveness.

There are two basic approaches to ANC. In the first, the original sound is processed and injected back into the sound field in antiphase. The second approach is to synthesize a cancelling waveform. In this approach, no prior knowledge of the original sound is needed.(4,5)

Theoretical and experimental studies have employed calculations done by using both algebraic and computer algorithms employing deductive or causal analysis. Physical geometry has been shown to be important to the effectiveness of ANC. Precise mixing of the cancelling sound field with the original sound field is necessary to achieve a high degree of attenuation. The phase and amplitude of the controlling and original waves must match closely to achieve useful attenuation. Analog and digital control systems utilizing adaptive and open-loop methods have been developed to track and process noise fields. Active filters may be configured to fit given applications; adaptive systems may operate by either trial and error or deterministic algorithms.

These control systems have many difficulties to overcome in order for ANC to gain wide acceptance. Some of these difficulties are related to airflow, temperature, and the formulation of accurate transfer functions.(4) Digital adaptive controls have been shown to be best suited to noise fields where the transfer function is highly dependent on varying parameters. This need for high precision in the transfer function has shown that superposition poses problems to the performance of ANC systems in addition to the limitations caused by the electronic circuits themselves. More general applications call for multichannel systems. However, multichannel systems have the inherent problem of instability caused by the mutual interference of the channels.(6)

If one takes the original and controlling sources to be point sources combined in one point, and the sources are located within a quarter of a wavelength, an overall area of spatial noise reduction will result. Theoretically, it is then always possible for ANC to achieve a zone of quiet, although this zone is usually small, in a diffuse sound field.(7) In actual application, generating a secondary diffuse wave field at some arbitrary point does, in fact, create a localized zone of attenuation. The pressure away from this zone will, in general, be raised because of the inherent spatial mismatch between the wave fields. Much work in ANC has been focused on developing controllers capable of matching the primary and antiphase wavefields with high precision. Self-adaptive systems have shown superiority in dealing with repetitive noise. This type of controller makes use of information from the previous cycle. This benefit of "negative time"(5) in which to generate the cancelling waveform has been effective in dealing with problems of spatial mismatch and instability. The adaptive controller does this by adjusting its output waveform to minimize the residual error at its input.

Pipes, Ducts, and Turbulent Flow

Active control of noise associated with turbulent flow in pipes and ducts is the largest research area in the field of ANC. It has been in this area of noise in ducts where much work into the actual mechanism involved in ANC and the causal versus noncausal aspects of system controllers has been done.

No analytical model has, so far, adequately described the acoustic mechanism involved in power flows associated with primary and control wavefields in ducts.(8) Most work to date has described the mechanism as one of phase cancellation. That is, the attenuation is caused by destructive interference between the primary and controlling wavefields. Other researchers have put forward the idea that the cancellation is actually a reflection of the primary wave at the secondary source. This reflection is caused by an impedance change at the secondary source from the sound pressure null created in front of the secondary source. Still other investigators have demonstrated analytically that two secondary sources will completely absorb all incident energy from the primary source.(8) This premise considers an idealized case without considering effects from spatial mismatch.

A fundamental problem with the foregoing is that most researchers have employed a model that places the primary source in the plane of the duct wall. A more useful approach would be to model the primary source in the plane of the duct cross-section. This gives a model with no phase variation across the face of the primary source.

Another major drawback of existing models is a lack of success in simultaneously measuring both primary and secondary source acoustic power flows and impedances. This has left most models unverified experimentally. Verification requires the measurement of both the net power flow down an anechoically terminated duct and the contributions from the source.

A more complete model for ANC in a duct is to view the attenuation as not simply a global cancellation phenomenon but rather a combination of one, two, or more physical processes: that is, an unloading of the primary source field and, hence, a reduction in its radiated power and impedance. Also, the secondary source can be shown to absorb some or all of the primary source's acoustic energy.(8)

Concerning the above, it has been proposed that multisecondary source systems are more effective for the task of ANC in ducts. This allows for a greater range of adjustment of phase angles, volume velocities, and secondary source locations. The multisecondary source system also has advantages in dealing with geometric aspects of active attenuation in ducts. If one frequency plus a few harmonics is the main noise problem, as is often the case with fan noise in a duct, then the positioning of secondary sources is of prime importance for effective attenuation.

A major consideration in the application of any ANC system for controlling duct noise is the design of the electronic controller. For effective attenuation to be realized, the optimal transfer function for the controller to implement must be determined. This transfer function can be expressed as the combination of measurable transfer functions comprising the primary wave field.[9] Two effective algorithms for modeling these transfer functions are the Feintuch algorithm and the Wiener-Hopf integral equation.[9,10] Dr. L.J. Eriksson[11] is a pioneer in the use of the Feintuch algorithm in developing adaptive controllers for ANC systems. This work is focused on both phenomenological and applied aspects of the field.[11–15] Much of the success that ANC has enjoyed in silencing noise in ducts can be traced to this work.[11–15] A series of papers has shown that use of the Feintuch algorithm requires the controller to employ frequency domain-based optimization theory[9] and hence a causal relationship. However, the dilution produced in the frequency domain of random primary fields often requires noncausal response from the secondary source.[8–10] An equivalent problem can be formulated utilizing the Wiener-Hopf equation to model the time domain with an optimal causal relationship between the primary and secondary sources. The solution to this equation can be found by using numerical techniques[10] and is, therefore, ideal for implementation in a digital controller using these techniques in discreet time.[9,10]

A further look at the problem of a causal versus noncausal controller requirement reveals that for a number of proposed ANC applications, the ideal controller is required to have a transient response that starts before the input is applied.[16] This then is decidedly noncausal. Because it has been previously shown that to suppress noise traveling along a duct, the controller should be causal to first approximation, a paradox exists. If controlling the wave in both directions from the primary source in a duct to minimize its power is desired, then the optimal controller again becomes noncausal.[10,16] Though it would appear that this conflict between causal and noncausal controller requirements would prevent practical application of ANC systems, it is important to bear some points in mind. First, even for a white noise–driven primary source, an optimal causal controller exists that will still give some reduction of power output.[16] Second, a self-adaptive controller capable of implementing a transfer function depending not only on the geometry of the primary and secondary sources but also on the autocorrelation properties of the primary source volume velocity will be able to deal with the causal versus noncausal aspects.[8–10,16]

Having discussed the physical mechanisms and controller requirements, it is useful to look at the types of experimental systems being utilized in current research efforts. To date, ANC systems have employed a one- or two-microphone sensing technique, depending on whether the system is synthesizing the controlling field or injecting the original noise back into the field. In a single-microphone system, a synthesized controlling field is output from n-sources to attenuate the primary noise field at the microphone location. The microphone senses the resulting attenuated field and sends any error caused by spatial mismatch to the controller for adjustment. The dual microphone system operates essentially in the same way as the single-microphone system. The main difference is that the second microphone is placed close to the primary source to detect the primary noise and send it to the controller for processing before it is reinjected into the noise field.[12,17,18]

The number of secondary sources utilized in ANC systems varies widely from researcher to researcher. Both single- and multisource systems have advantages and limitations. As more work is done in the field of ANC and issues of geometry, stability, and spatial matching become better understood, a consensus should form as to whether single- or multiple-source ANC systems are more desirable for a given application.[12,13,19]

Propellers, Fans, and Vibrating Plates and Shells

Noise associated with fans and propellers can be divided into two distinct categories. The first is noise generated directly as the blade passing tone fundamental and harmonics. The second is noise generated as a result of blade tip turbulence inducing vibration in structures. The application of ANC to the attenuation of both categories of noise has been responsible for much work in the field. This is principally because of its relevance to the control of helicopter and other aircraft noise. This is evidenced by the fact that much of the research is funded or conducted by the U.S. Air Force, U.S. Navy, and the National Aeronautics and Space Administration Langley Research Center.

ANC is applied to problems associated with direct blade tone noise, such as fan noise, utilizing similar system configurations as outlined in earlier sections of this paper.[20,21] In the case of fans and propellers, specific fundamental and harmonic tones are processed with either adaptive or filter-based controllers, injecting an antiphase secondary field into the primary sound field. Typically, the frequencies to be attenuated are found in the range of 200 to 1500 Hz.[20] Variable parameters found in typical experimental applications include impeller loading conditions, blade diameter, impeller geometry, and duct geometry.[20,21] This class of noise problems exhibits behavior that is periodic, giving a more readily measurable transfer function. Attenuation is most effective if the secondary sources are located within one-quarter wavelength of the primary source.[20–22] This attenuation can be achieved by both acoustic monopoles and multisource systems.

The problem of noise induced by vibration in a structure is one area where ANC overlaps with active vibration control. In these problems, transducers are used in place of loudspeakers to cancel vibration, not sound, in the structure. This cancelling of vibration attenuates noise caused by interaction at the coupling between space and structure. Work has shown that significant attenuation is achieved by identifying and cancelling (dampening) the fundamental and main harmonic excitations in the structure. The actual attenuation level is dependent on the frequency of excitation and the coupling between the structure and the acoustic space. The limitations on the behavior of the noise generated by this acoustic coupling is termed *interface model filtering*.[23] A single acoustic mode will tend to dominate the generation of the primary sound field.[23] ANC systems, therefore, need only to process this single mode to achieve effective attenuation. Actual attenuation levels are limited by the amount of acoustic energy propagated axially from the source. Therefore, the most effective control is achieved with primary excitations showing strong axial decay in the shell.[23]

Fortunately, this is the case in many physical problems for frequencies at which structural propagation of waves becomes significantly damped.[21–23]

Broad-Band Noise and the Three-Dimensional Problem

Active cancellation of both broad-band noise and noise propagated in three-dimensional spaces has posed the most intractable problems in the field. Previously discussed limitations—such as noncausality, stability, and spatial mismatch—are magnified by this class of noise environment. Additionally, it is with the application of ANC to three-dimensional space and broad-band noise that the problem of the infinite gain controller requirement is confronted. To compound this problem, these physical limitations have only recently been addressed in the literature.

As stated in earlier sections, the secondary sources need to be located within one-quarter wavelength of the primary source for significant attenuation to be achieved. However, in the case of broad-band or three-dimensional noise, where distinct phase changes occur across a primary source, it has been shown[24,25] that the secondary sources will have to be positioned near each antinodal point. This implies that many secondary sources will be required, thus inviting problems associated with stability and spatial mismatch.

There is a fundamental flaw with the inference from Huygens' principle as a model for ANC in three-dimensional spaces. That is, to reproduce exactly a sound field as the primary field in a three-dimensional space, the pressure and velocity at every point in the space for the secondary sources need to be the same as for the primary source. Put another way, the secondary sources must be infinitesimal, continuous, and determined uniquely.[26] Because in practical application all sound sources have some volume, then it follows that actual attenuations achieved will be far field or zones of quiet.[26–28]

Limitations are placed on ANC in three-dimensional spaces because of distortions caused by reflections in the reverberant space.[27,28] This distortion points to the need for shielding of detection and error microphones to ensure accuracy. The reflections suggest that combining traditional passive noise control techniques, such as absorptive materials, with ANC will increase the level of effectiveness of active attenuation in reverberant spaces.

As has been discussed in previous sections, the controller design is of critical importance in dealing with the various limitations placed on ANC of broad-band and three-dimensional noise. It is of the utmost importance that the design of the transfer function employed maximizes the stability of the system.[27] Adaptive algorithms and hardware and inverse filtering techniques[28] have been employed to meet controller requirements. For certain combinations of detector and cancellation points, with respect to the primary and secondary sources, an infinite gain controller requirement exists.[27] This requirement is defined as a locus of points in which a controller must have infinite gain in order to achieve attenuation. This means that spatial areas will exist in which the controller output must be infinite in respect to its input. Although only recently proposed in the literature,[27] the infinite gain controller requirement reinforces the premise that ANC in broad-band and three-dimensional applications will be restricted to far-field attenuation or small spatial zones of quiet. This will hold until such time as control mechanisms are developed in which this requirement is not inherent.

To date, experimental trials[25–28] have yielded attenuation levels of about 4 to 18 dB. These actual levels of attenuation are in stark contrast to the 100% attenuation that is theoretically possible. This actual range of attenuation is significant, however, and points to the feasibility of ANC for this class of noise problems as systems are designed to deal more effectively with the limitations inherent in broad-band and three-dimensional noise applications.

Personal Hearing Protection

Application of active attenuation techniques to personal hearing protection has been the area of ANC where the majority of actual field applications have been focused. The development and application of active noise cancelling earmuffs has been spurred by interest on the part of the military to come to grips with such harsh noise environments as aircraft carrier flight decks and interior noise in helicopters. In the case of the latter, the noise environment can reduce crew operating shifts to 3 hr.[29]

The literature has shown that active attenuation in earmuffs is best suited to the control of periodic, low-frequency noise.[29,30] These systems are typically designed to place the actual cancellation point near the eardrum. In addition to noise attenuation, these earmuffs can be designed with enough headroom to allow the transducer to not only deliver the cancelling signal but also to deliver undistorted speech communication.[30] This gives noise-cancelling earmuffs superior capabilities for the applications mentioned previously. The theory behind ANC earmuffs is relatively straightforward. Given that the attenuation is to be achieved at the entrance to the ear canal, then the total acoustic pressure can be expressed as the sum of the acoustic pressure of the noise and the open-loop transfer function.[31] This open-loop transfer function is the key to the operation of the system. The open-loop transfer function can be expressed as the product of the acoustic transfer function, the transfer functions of the microphone and headphone, and the complex gain of the control electronics. By utilizing the ratio of the total acoustic pressure to the acoustic pressure of the noise as the operational parameter of the system, the larger the product (open-loop transfer function), the smaller the pressure ratio and, hence, the greater the attenuation.[31] The product is a complex number. Therefore, if the product becomes negative, the pressure ratio is greater than one, causing the noise to be enhanced and the system to become unstable; stability becomes the prime mechanism limiting the attenuation levels that can actually be achieved.[29–31]

CONCLUSIONS

This paper has shown that although great progress has been made toward the applicability of active noise control to real-world problems, much work is yet to be done. The recent quantification of several fundamental physical limitations has served to expand the field in terms of the number of active researchers while constraining the field in terms of workable systems. The literature clearly shows that the development of highly adaptive and stable controllers is the prime factor in large-scale application of active noise control. Active noise control represents the future for noise control engineering. However, with fully 75% of the work in the field of a theoretical and experimental nature, the future is still somewhat distant.

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