Recent Advances in Active Noise Control

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Recent progress in the field of active noise control is reviewed. The advent of the digital computer and subsequent speed and capacity improvements have made active noise control more practical and have encouraged rapid advancement in research. Several surveys of research have been done in the past, so emphasis is placed on the newest and most innovative research. In particular, the advancement of research on active noise control during the decade of the eighties is reviewed.

Introduction

ACTIVE noise cancellation is the canceling of a sound wave by the addition of an inverse sound wave. Active noise cancellation has been studied for some time now. The physical principles behind active noise control have long been understood, but the first formalization of the method appeared in the form of a patent by Lueg[1] in 1933 in Germany. He filed a U.S. patent in 1934.

Although Lueg's patent was not very extensive, the ideas he developed for the cancellation of single frequencies, sources in open space, and complex waveforms form the basis of modern research in active noise cancellation. Development of the technology since Lueg's time has gradually accelerated.

The advent of the affordable digital computer during the 1980s has made active noise cancellation more practical as a method for noise control. As computational speed barriers are pushed back, it becomes possible to achieve better models and methods for active control. Computers have also facilitated the development of adaptive active cancellation techniques.

As several surveys of active noise control have been done in the past,[2-6] emphasis will be on developments that occurred during the 1980s. Specific attention will be given to the most recent results. Every attempt has been made to be complete in the coverage of the topic and to give appropriate credit, but inevitably there will be omissions.

Basic Principles

The main physical principle behind active sound attenuation is the destructive interference of two sound waveforms. The generation of the proper interference signal in the proper position at the right time, however, makes the realization of a useful active noise canceling system difficult. The following principles are basic to active noise attenuation research.

Young's Principle

Young's principle of interference (Fig. 1) is the basis of active noise control. It simply states that a pressure wave propagating in space can be canceled by the addition of the inverted waveform. This effect is reflected in the figure for a simple tone. For simple tones, the inversion is simply a 180-degree phase shift. The theory is simple, but its application suffers from many difficulties.

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In order to cancel a waveform effectively, it must be matched exactly at every point along its path. Since any sound source will have its own radiation pattern, an exact match is practically impossible to achieve.

Huygen's Principle

Huygen's principle (Fig. 2) is based on Young's principle but provides for an approach to wide area noise reduction. Huygen's principle considers a domain completely separated from a set of sound sources by a closed surface. Huygen states that the sound field at any point within the surface produced by a sound source outside the surface can be reproduced exactly by an array of secondary sources distributed along the surface.[7,8]

Around a Zone

It follows that the sound at every point within the surface can be reduced to zero if the secondary sources generate the inverted version of the signal incident on the surface. Thus, a "zone of silence" can be created within the closed boundary by an appropriate distribution of the secondary sound sources. This method provides a means of sound attenuation for a finite area regardless of the type of sound outside the boundary.

Around a Set of Sources

An alternate application of Huygen's principle is to enclose the sound sources with the Huygen surface. By generating the inverted signal at the surface, sound radiation can be attenuated. This approach allows a complex and relatively compact sound source, such as an engine, to be silenced by surrounding it with an array of secondary sources along a Huygen surface.

Since Huygen's principle relies on an infinite number of perfect point sources on the Huygen surface, it is not practically realizable. A reasonable approximation can be made, however, by placing a finite number of discrete sources in an array around the surface. If the sources are close enough (one-

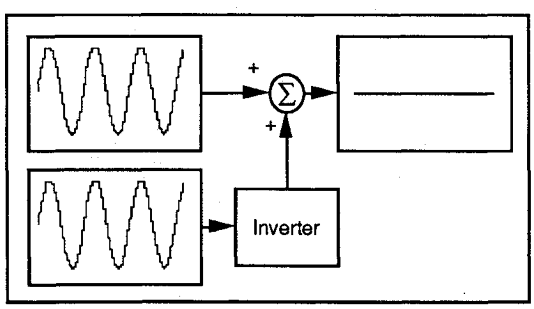

Fig. 1 Young's principle. The addition of inverse sound waves will produce silence.

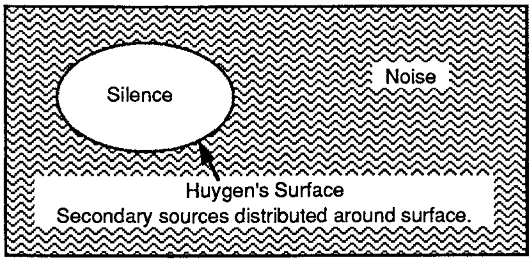

Fig. 2 Huygen's principle. Surface encloses "zone of silence." Secondary sources on surface produce inverted model of noise field.

half the wavelength of the highest frequency to be canceled), the sound can be effectively attenuated.

Liu and Ma[9] studied the field-fitting requirements in free-field active noise control. Field fitting is the process of placing secondary sources so as to best match the sound field of the primary source. They were able to achieve noise reduction levels of 20 dB using six secondary sources.

Several studies have been done with different arrangements and numbers of sources. Some have surrounded the primary source,[7,8,10] whereas others have created active sound baffles with a wall of sources.[11] These studies verify Huygen's principle but also illustrate its limitations when implemented with a finite number of secondary sources.

Previous Research

Research in the past has been mostly confined to a few areas of interest that were productive. Limitations on computer speed and the complexity of propagating sound have partially dictated the focus of active noise cancellation research. The following is a summary of research to date.

Duct Noise

The cancellation of duct noise has long been an emphasis in the field of active noise cancellation. There are several reasons for this. Perhaps the most important is that ducts act as waveguides and a sound wave propagating in one dimension can be studied. This is because below the cutoff frequency, the plane wave mode is the only propagating mode. It is much easier to deal with one dimension than three, and it is assumed that success in one dimension will provide a basis for success in free space.

Also significant in duct research is the fact that the flow impedance characteristics of active noise control can be studied. One of the chief advantages of active noise control is the fact that it does not have the flow impedance problems of passive control. Active noise control in ducts has provided concrete evidence for this claim.

A myriad of papers have been written on active noise control in ducts. They cover such varied topics as energy conservation (see Refs. 12 and 13), higher order mode cancellation,[14] nonplanar waves,[15] turbulent flow,[16] adaptive control,[17] and general active noise cancellation in ducts.[18–25]

In most cases, significant noise reduction (up to 20 dB) can be achieved for frequencies up to 500 Hz. The frequency limit is imposed by sampling/processing speed limitations and the failure of the plane wave model for higher frequencies as well as the duct dimensions.

Cylinders

Another area of research that is fairly well defined is active noise control in cylinders. The motivation for this type of work seems to be primarily as a simplified model of an aircraft fuselage.

The cylinder is elastic and is set in motion by external sources. This configuration is designed to simulate propeller noise transmitted through the fuselage walls into the aircraft cabin.

Several configurations have been used for the active control of the noise inside the cylinder. Silcox et al.[26] and Lester and Fuller[27,28] have investigated the use of four secondary sources placed at 90-deg increments around the cylinder in the same plane as the primary source. They found that sound can be significantly attenuated over most of the cross section with four secondary sources. Increasing the number of sources improves the results. An example of a contour plot of the effects of active noise reduction in a cylinder is shown in Fig. 3.

Bullmore et al.[29] have investigated alternate secondary source placement. They determined that, if it is impossible to place the secondary sources close to the primary sources, it is still possible to achieve good reduction provided the sources are placed so that they couple efficiently to the modes most dominantly excited by the primary source.

One popular experiment involves positioning secondary canceling sources along the walls of the cylinder in order to attenuate periodic noise generated outside the cylinder. These experiments correspond to the reduction of cabin noise due to airplane propellers.[30] It has been shown that such a configuration can reduce noise levels within the enclosure by more than 13 dB at certain frequencies.

Fuselage

Research in active control in an aircraft fuselage is a natural extension of active control in a cylinder. There have been a few papers written which investigate situations that are more practical than the cylinder model.[31,32]

Salikuddin and Ahuja[33] have investigated the transmission characteristics of the fuselage surface. They noticed significant noise reduction in the interior of the aircraft by using an array of four secondary sources mounted on the fuselage wall. As an added benefit, their arrangement could provide decreased structural fatigue (Fig. 4).

Salikuddin et al.[34] placed a secondary source in a fairing attached to the wing of a 1/10 scale model plane and placed test microphones in an array pattern on the fuselage. They noticed attenuation levels of 9–17 dB for simulated propeller noise and 8 dB for a scale model test with an actual propeller.

Fans

Another natural application of active noise control is in attenuating the noise produced by fans. Fans produce a low-frequency tone at the blade passage frequency and broadband noise due to the forced air flow.

Active noise control has been especially effective in reducing pseudo-periodic noise. By synchronizing the noise canceling apparatus with the blade passage frequency, it is possible to predict the next period quite accurately. Once the next cycle is known it is a relatively simple matter to invert the signal and cancel the noise.

In experiments done by Koopmann et al.[35] on active noise control of centrifugal fans, the results were impressive. They were able to consistently reduce the noise by 10–20 dB at the blade passage frequency. Similarly, experiments done by

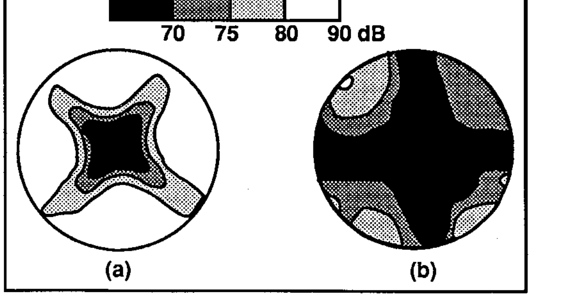

Fig. 3 Contour plots of the sound pressure level in the source plane at 475 Hz: a) primary field; b) composite field.[26]

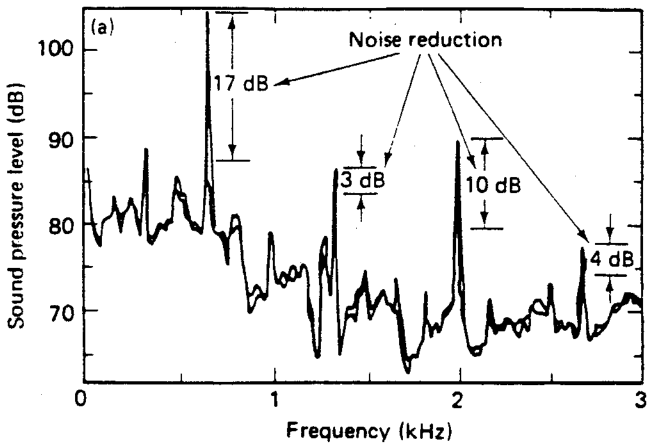

Fig. 4 Reduction of propeller noise. Localized reduction of model propeller noise at a single location.[33]

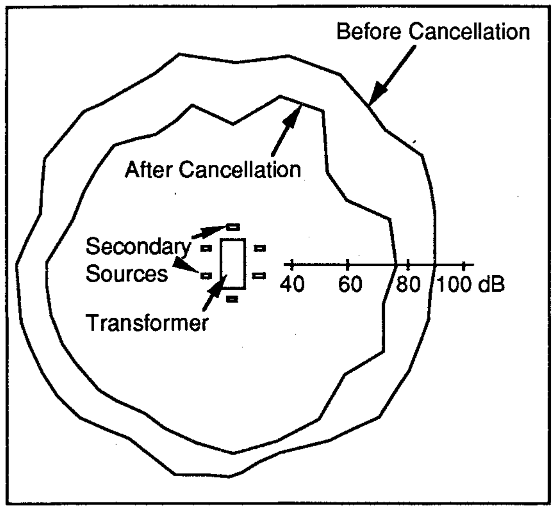

Fig. 5 Transformer noise reduction. Variation in SPL at 125 Hz at 2 m distance around transformer using 26 tripoles.[7]

Quinlan[36] on small axial-flow fans showed attenuation levels of more than 10 dB (see also Ref. 37).

This area of active noise control is fairly well developed. There are several commercial systems available that are designed to reduce fan noise, especially in heating and air conditioning systems.

Transformer Noise

A problem similar to that of reducing fan noise is the problem of reducing low-frequency hum due to large transformers. The basic frequency of such signals is usually easy to obtain. Once this frequency is obtained, active noise control can be applied to the periodic signal as it is in the control of fan noise. Transformers have the added advantage of not producing significant levels of broadband noise. Angevine et al.[38] have studied the active control of low-frequency hum in depth, and have shown that active control can be very effective in reducing hum. Attenuation levels of 16 dB at 125 Hz are typical (Fig. 5).

The main problem in reducing transformer noise is preventing wide area propagation. This is usually achieved by surrounding the transformer with an array of Huygen sources. In Angevine's experiment, 26 secondary sources were used.

Transmission Path Positioning

In active noise control, there are several approaches to noise reduction. The noise can theoretically be canceled at any position along the transmission path. There are advantages and disadvantages to each approach. A summary of these methods is given below.

Near Source

It is usually most desirable to cancel the noise at the source. This prevents the noise from propagating in free space and avoids its attendant complexities. Also, it has been shown by Nelson et al.[39] that, to effectively reduce sound radiation, the primary and secondary sources must not be separated by more than half the wavelength of the highest frequency to be canceled. Often, however, this positioning is prevented by extreme environmental conditions (such as intense heat or high-speed air flow). Sometimes, the source of the noise cannot be specifically localized (as in radiation from a panel[11]). Near-source cancellation is usually achieved by placing one or more sources in close proximity to the noise source and in the path of sound transmission.[40,41]

Enclosures

Enclosures provide another effective application of active noise control. Enclosures illustrate a natural application of Huygen's principle. Either the sound generated by a noise source within the enclosure is prevented from radiating or sound outside the enclosure is prevented from entering.

Enclosures have several advantages as environments for active noise control. First, they limit the scope of the problem to a well-defined space. Second, they allow for control of the properties of the space (i.e., acoustic absorbancy, environmental conditions, and physical dimensions). Finally, they allow for the placement of noise-canceling equipment in a nonintrusive manner.

One of the characteristics of enclosures is that they have resonant frequencies. Extensive research has been done on the active control of noise within harmonic enclosed sound fields by several researchers, especially those at the Institute of Sound and Vibration Research.[29,42–45] Although one of the drawbacks of enclosures is the fact that they are generally semi-reverberant, it turns out that the reverberation frequencies are usually controllable with active noise cancellation.

The inverse problem is to prevent noise generated within the enclosure from radiating. This generally means enclosing a complex noise source, such as a large power transformer or an engine, and positioning an array of Huygen sources in the walls of the enclosure. This method has been successfully demonstrated by Angevine[38] in the reduction of large transformer noise.

Single Point

One of the most effective approaches to active noise minimization is the cancellation of noise at a single point. Although the applications for this idealized case are limited, almost perfect results are achievable. The method involves placing the microphone at the spatial position for noise attenuation and minimizing the noise at that point.

Active noise cancellation at a single point has been done successfully by Elliott et al.[46] In this experiment, a pure tone source was radiated and picked up at the microphone position. The secondary source was then used to model the inverted signal and the error was minimized at the microphone position. Attenuation levels of more than 10 dB were observed within a diameter of about 1/10 of the wavelength of the excitation frequency from the microphone. The sound pressure outside this region, however, was considerably worse than without the secondary source. To obtain reasonable noise reduction over the whole field, multiple microphones must be used.

Another successful application of active noise cancellation at a point involves the use of headphones.[47] A passive headphone is used so that sound may pass through the back of the headphone and be heard. A miniature microphone within the earphone is then used to detect the error signal. The error measurement is usually synchronized with periodic noise sources and an inverted model of the interfering signal is generated. The nonperiodic signal is then audible.

Free Field

A more difficult, but eventually more useful, application is the active cancellation of noise in a free-field environment. This method relies on Huygen's principle. Either the noise source is surrounded by secondary sources to prevent wide area radiation or a "zone of silence" is surrounded to prevent the intrusion of propagating sound.

Free-field noise cancellation is certainly the most difficult application of active noise control to implement. This is due to that the fact that, in order to effectively cancel the noise at the Huygen surface, the secondary sources must not be separated by more than a half wavelength of the highest frequency to be canceled.[39] Since this is generally not possible, compromises must be made.

Another difficulty with the free-field Huygen surface method is the number of sources that must be controlled. While there are algorithms for the minimization of multiple errors,[48–51] each error signal considered increases the amount of processor time required. This limitation can be overcome to some extent with the use of independent dedicated controllers, but this increases the cost of the system.

Nevertheless, some experiments in the free-field active cancellation of noise have provided some encouraging results. Nelson et al.[39] determined the power requirements for such a system and provided an algorithm for quadratic optimization.[52] Short[53] effectively used free-field active noise attenuation on low-frequency sources. With one secondary source, maximum attenuation levels of 8 dB were observed. With two sources, the maximum attenuation was 12 dB.

Sensor and Source Positioning

A key consideration in the design of an active noise control system is the positioning of the secondary sound sources and microphones. The following summarizes the most successful configurations to date.

One-Dimensional and Ducts

As mentioned earlier, ducts have the advantage that for many purposes they can be modeled as one-dimensional acoustic waveguides. This dimensional simplification makes duct analysis attractive and limits the microphone/speaker configurations (Fig. 6).

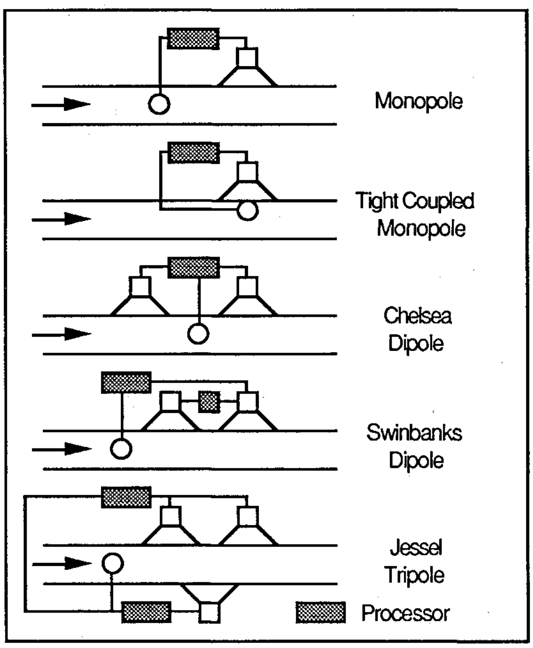

Fig. 6 Duct configurations. Active noise attenuators for ducts.[5]

The monopole configuration is the simplest. A single speaker and microphone are used. The microphone is placed upstream from the speaker. It thus measures the signal to be modeled and inverted at the speaker. An in-depth study of the monopole configuration has been done by Eghtesadi.[54]

The tight-coupled monopole or virtual Earth system is identical to the regular monopole except for the fact that the microphone is placed in close proximity to the secondary source. There are a couple of papers on the tight-coupled monopole by Eghtesadi[55] and Hong et al.[56]

The dual monopole or Chelsea dipole configuration places a single microphone between an upstream speaker and a downstream speaker. The reason is to prevent an upstream propagation of the signal which might affect the flow. A paper by Eghtesadi[57] explains the use of the Chelsea dipole configuration.

Two other configurations, the Swinbanks dipole and the Jessel tripole, involve two and three secondary sources, respectively. Both of these systems require two electronic processing units. Their complexity is designed to prevent the canceling waveform from propagating upstream. In general, the key reason for the variety of configurations is the need to control acoustic feedback.

Three-Dimensional

The three-dimensional active attenuatoin of sound makes use of Huygen's principle. As previously explained, a Huygen surface, made up of a suitable array of sources, can be placed around the noise source to create an inverted model of the sound just inside the surface or a Huygen surface may be placed around a "zone of silence." The sources on the surface are then used to create an inverted model of the sound field just outside the surface.

A number of papers have been written on the applications of Huygen surfaces in the minimization of sound in three-dimensional sound fields.[5,9,38,51,52]

Implementation Methods

Once the configuration for speaker and microphone placement has been determined, the method of implementation for active noise control must be considered.

Geometric Phasing

Geometric phasing is the simplest method of active noise control. It effectively inverts the signal at the speaker location by positioning the speaker downstream from the microphone. The signal from the microphone is delayed and inverted so that it reaches the speaker at the same time as the original sound. Since the electronic path to the speaker is much faster than the acoustic path, the signal takes a shortcut and an effective "negative time" version of the signal is available at the speaker, assuming the signal does not change significantly between the microphone and the speaker.

Filtering

Filtering is the usual method used to extract the signal of interest from a noise-corrupted version of the signal. In active noise control, however, the noise rather than the signal of interest is extracted so that it can be inverted and used to actively cancel the noise. Wiener filtering is the method commonly used to separate the noise and the signal. In a Wiener filter, the combined noise and signal of interest (the signal of interest may be silence) are sampled (Fig. 7). Then a model of the noise is created synthetically by using a priori information about the noise or statistics from the sampled noise. This model is then inverted and added to the original noise corrupted signal. Thus, the noise is removed from the desired signal (or silence). For a detailed description of this method see Ross.[58]

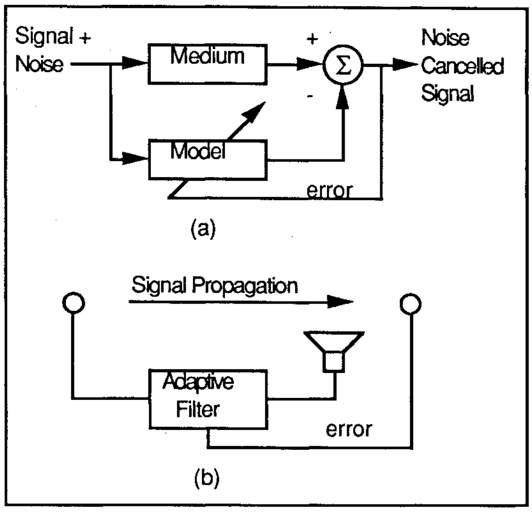

Fig. 7 a) Adaptive Wiener filter; b) active noise control application of an adaptive Wiener filter.

Synchrophasing

Synchrophasing has been used effectively in the active minimization of periodic noise such as that produced by engines and transformers. In this method, a synchronizing signal is sent to the active control system. This allows the system to get an accurate prediction of the next period of the signal from the current period. This signal can be injected inverted into the signal path to reduce the noise. Jones and Fuller[59] have used this method to reduce propeller noise.

Adaptive Filtering

Adaptive filtering is the implementation of a filter which is periodically adapted to track changes in the system. Adaptive filtering is the most generally effective method of active noise control. It has the advantages of automatic minimization and automatic adjustment to changes in the system over time.

An adaptive filter is created by using two microphones instead of one. The first microphone is placed upstream (with respect to sound propagation) from the loudspeaker to get the noise-corrupted signal. The other microphone is placed downstream from the speaker to get the error signal. The error signal is simply the observed, noise-canceled signal. It should ideally be silence.

The adaptive filter creates a model of the corrupting noise and outputs it at the loudspeaker. The error microphone samples the noise-reduced signal and determines the error. This information is then fed back to the adaptive filter and the filter model is adapted to minimize the new error.

Using Wiener filtering techniques, this method is capable of extracting signals from background noise within the same frequency bands if the noise alone is sent to the model. Its effectiveness is limited by the complexity of the adaptive model. There are numerous articles on adaptive active noise cancellation. For a good overview, see Refs. 17, 48–51, 60–66.

Although most research in the area of adaptive active noise control has been done using finite impulse response (FIR) filters, there has been some work done with other digital filter models. Infinite impulse response (IIR) filters, in particular, have been studied by Eriksson and Allie.[67,68]

Stevens and Ahuja are also researching different adaptive algorithms and comparing their performance in active noise suppression applications. A computer simulation has been implemented to facilitate the comparison. The convergence performance of the least mean squares (LMS) algorithm is shown in Fig. 8. The adaptive system is attempting to cancel white Gaussian noise which has been delayed, attenuated, and further corrupted by a small amount of additive noise.

As can be seen, the noise is effectively canceled after about 150 samples of the signal. The residual noise is a result of the unpredictable noise accumulated between the upstream microphone and the downstream (error) microphone (see Fig. 7).

Although the LMS algorithm is the simplest and most popular, there are several other algorithms that have potentially better performance. As an example, consider the recursive least squares (RLS) algorithm. This method uses the exact signal values rather than statistics based on the signal values in its computation. The result is a much quicker convergence rate (Fig. 9). However, there are increased computational requirements with the RLS method.

There are several techniques that may be used to reduce the computational requirements. The Kalman[69] approach is one that significantly improves the calculation time for the RLS adaptive filter. It does this by using an efficient method for recursively updating a "correlation" matrix inverse.

Other adaptive routines are also being studied by the team members of the second author (K. K. Ahuja). Fast transversal filter (FTF) algorithms, infinite impulse response (IIR) adaptive filters, and adaptive lattice filters are being numerically and experimentally evaluated in active noise control applications. Typical applications include echo cancellation in auditoria, resonance suppression in ducts and enclosures, automobile exhaust noise suppression, engine test-cell resonance suppression, impulsive noise source attenuation, and transducer signal-to-noise ratio enhancement.

Time Variance

In many applications, the features of the noise being attenuated will change over time. This may be due to wear on an engine, change in environmental conditions, fatigue of components, or any number of other possibilities. It is important, therefore, to consider this when implementing an active noise control system.

If the changes over time will be minimal, it may be reasonable to manually adjust the system periodically. If the noise characteristics change significantly, however, it may be best to use an adaptive active noise control system since it will adjust to these changes automatically. Eriksson et al.[70] have written a paper which considers active noise control and time variance. Attenuation levels of 30 dB were attained in reduction of diesel engine noise and centrifugal fan noise (Fig. 10).

Noise Control Through Active Control of Flow Phenomena

Another interesting experiment on active control of sound in enclosures was performed by Sunyach.[71] Periodic sound produced by a flow over a cavity was reduced by placing a secondary source at the bottom of the cavity. Not only did

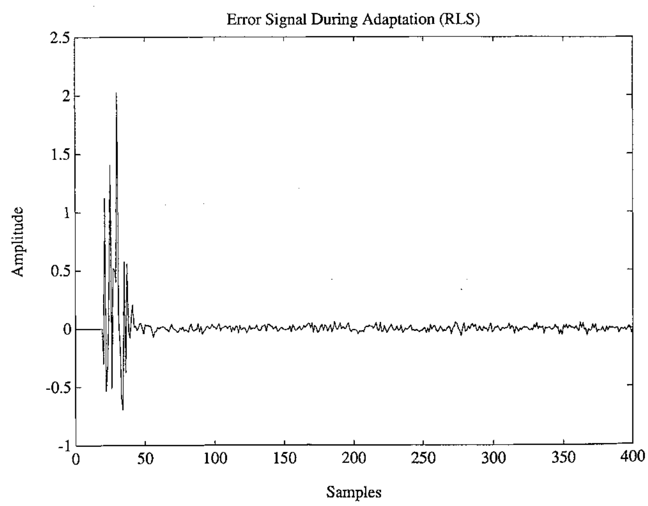

Fig. 8 Active noise canceling convergence characteristics of the LMS adaptive filter algorithm.

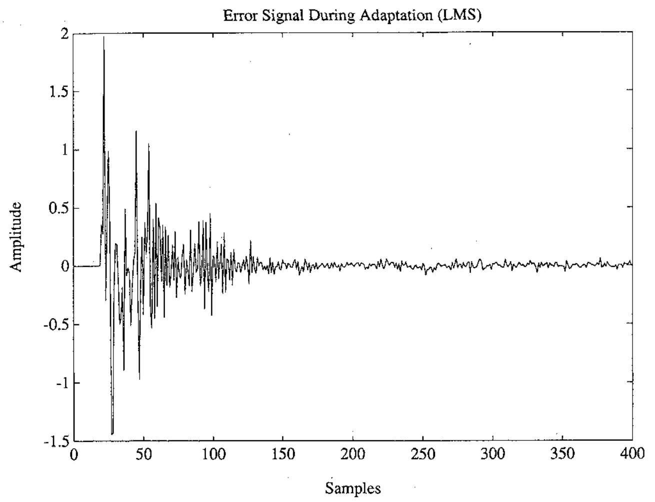

Fig. 9 Active noise canceling convergence characteristics of the RLS adaptive filter algorithm.

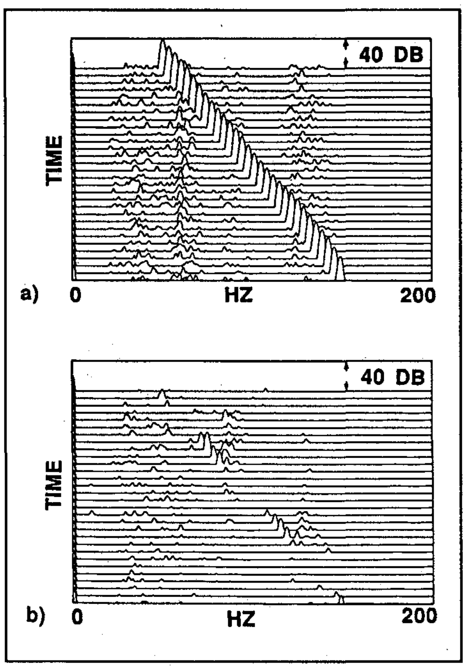

Fig. 10 Active noise reduction of a time varying source: a) uncanceled signal; b) canceled signal.[71]

this reduce the noise by up to 20 dB, it also reduced the turbulence of the surface flow.

Types of Noise

There are several types of noise that have been targeted by various active noise control techniques with varying degrees of success.

Single Frequency

The simplest type of noise is a single-frequency sinusoid. While not very practical for most noise reduction requirements, single frequencies help simplify analysis and make it possible to theorize about approaches to more practical active noise cancellation techniques. Single frequencies can be quite effectively canceled by all active noise control techniques.

Periodic

Active noise control has been especially effective in canceling periodic and quasiperiodic signals. Periodic signals are signals that are exactly repeated periodically. While pure periodic signals rarely occur naturally, they can be generated synthetically to provide simplified models of quasiperiodic signals. Quasiperiodic signals vary slightly between periods. Quasiperiodic signals can be considered as periodic signals with additive noise. An example of quasiperiodic noise is engine exhaust noise. The noise signal produced at the firing of each cylinder does not vary much between periods.

In active control of quasiperiodic signals, a sensor is usually connected to the noise source to send a synchronization signal to the active noise control system. Becuse the noise signal does not change much from period to period, an accurate image of the inverted signal can be predicted and injected into the signal path.

This method of active noise control has been used to effectively cancel noise produced by engines, fans, and other quasiperiodic noise sources.[72,73]

Narrow Band

Narrow-band noise is composed of frequencies concentrated in a relatively narrow range. This type of noise is more difficult to cancel with active control than a single frequency, but it is not as difficult as broadband noise. Active control can be especially effective as a means of controlling narrow-band noise if the noise band does not overlap the band of frequencies occupied by the signal.

Broadband

Broadband noise presents a more difficult active noise control problem. Since broadband noise is much more complex than other types of noise, it is more difficult to produce an accurate prediction of the noise at any position in time or space. Also, if there is a signal imbedded in the noise, it is not a trivial problem to cancel the noise without simultaneously canceling the signal.

Methods of active noise control for broadband signals are necessarily statistical in nature. The most effective approaches have been Wiener filtering and adaptive filtering techniques (described above). Eriksson et al. have successfully reduced noise below 250 Hz by up to 40 dB by using these techniques.[70]

Wiener filtering is effective because it provides a method for separating the signal and noise even if they occupy the same frequency bands. Adaptive filtering is popular because the statistics of the noise do not need to be known a priori. The adaptive filter continually updates its model to better match the desired signal. An adaptive filter minimizes maintenance requirements as well as noise levels.

Wiener filtering and adaptive active noise control are perhaps the most active areas of current research in active noise control.[70,74–78]

Other

Research in active noise control has produced valuable information on the cost and feasibility of active noise control as a noise attenuation alternative. Eghtesadi et al.[12] have done a study on the energy conservation advantages of a hybrid active/passive noise control environment in ducts. The active noise control techniques are used to reduce low-frequency noise without flow impedance, and passive methods are used to reduce the high-frequency noise. They found that better noise reduction and better efficiency can be achieved with such a system.

Other studies have compared the cost of active and passive noise control systems.[79–81]

Current Research

Research in active noise control is advancing at a rapid rate. Improved methods and new applications are constantly being discovered. Below is a sampling of some of the current research being done.

New Applications

Eghtesadi and Gardner[82] have been working on the design of an active muffler for internal combustion engines. Such a muffler could significantly reduce automobile noise while avoiding backpressure on the engine.

New Actuators

New actuators have also been studied. Fuller et al.[83] have investigated the use of piezoceramic actuators in the active control of structurally radiated noise. Piezoceramic actuators may be more efficient actuators in such a situation and would therefore reduce the cost of active noise control.

New Configurations

Kido, et al.[84] have studied alternate arrangements of sound sources in active noise control. More ideal source arrangements can make the realization of an effective Huygen surface possible. Also, if the limits of additional source placement can be understood, it can help direct the course of future research.

New Algorithms

One of the most active areas of current research is in the development of new or optimized algorithms. Most of the algorithms currently being developed are variations of adaptive filtering techniques. Sommerfeldt and Tichy[66] have developed a least-mean-squares-based adaptive control algorithm. Elliot and Nelson[48] have also developed algorithms for multichannel active control. This is important in the quest for a more effective realization of a Huygen surface. Ren and Kumar[64] provide a good presentation of adaptive algorithms for active noise control.

New Methods of Visualization

Ahuja and Stevens have developed a system for visualizing active noise control in a flexible cylinder (Fig. 11). A layer of powder (talcum powder, chalk dust, or glass beads) is laid in the bottom of a glass or plastic cylinder. When the tube is acoustically excited, the nodes and antinodes of the standing waves can be clearly visualized by observing the height of the vibrating powder. This technique allows one to qualitatively assess the performance of a given active control algorithm without installing a large number of microphones or implementing a microphone traverse system.

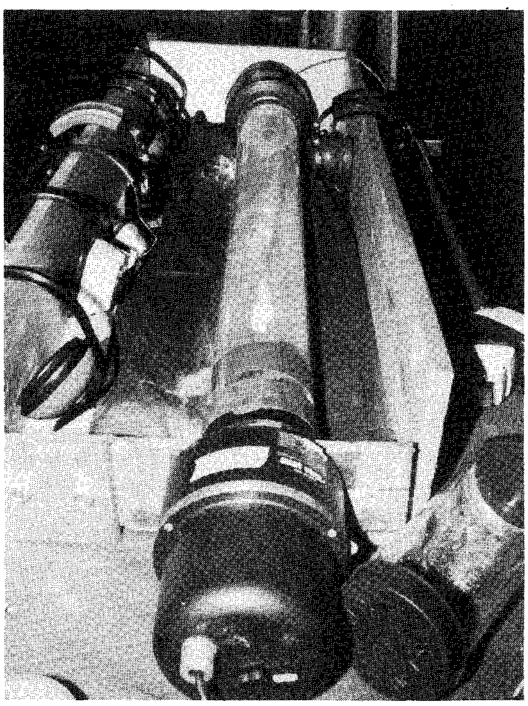

Fig. 11 System for visualizing active noise control in a cylinder developed by Ahuja and Stevens.

Commercial Feasibility

The commercial feasibility of active noise control can hardly be questioned. It is more cost efficient and more effective in noise reduction than typical passive methods. It does not impede fluid flow. It can reduce noise selectively, even when the noise and the signal occupy the same band of frequencies.

It is, however, not without its problems. Active noise control can be computationally expensive. It is difficult to create an effective Huygen surface. The closer a real Huygen surface is approximated, the more expensive it gets. Active noise control is also less effective at reducing high-frequency noise. The advantages, however, are impressive enough to provide a mandate for further research.

A study of hardware and software requirements for active noise control has been done by Allie et al.[85] and a more specific study of the requirements for adaptive active control has been done by Eriksson and Allie.[86]

Conclusions

Active noise control has become more and more popular in recent years. This popularity is due, in part, to the advancement of electronics and signal-processing techniques which take advantage of increased computer power. In particular, Wiener filtering and adaptive filtering methods have natural applications in active noise control.

Research in active noise control has also been driven by an increasing demand for improved noise environments. Manufacturers and consumers alike are interested in reducing the noise produced as a side effect of technology.

Active noise control is currently being implemented commercially in several forms. There are several systems available for reducing noise in air-conditioning and heating systems. Active noise control in automobiles is on the verge of commercial implementation. The commercial installation of active noise control in some aircraft is also imminent.

While the ultimate goal of effective selective noise attenuation over a broad band of frequencies has not yet been achieved, the goal is at least a bit more attainable now. With continued effort, the cases of success will accumulate and active noise control may emerge as the most effective means of noise reduction.

Additional Readings

See references 87–124 for additional reading.

Acknowledgments

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