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State-of-the-art in active noise control (ANC)

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Abstract

The paper reviews techniques of active noise and vibration cancellation. Early developments and recent advances are surveyed including the theoretical background. Some of the old and a myriad of new applications are referred to in the text.

1 Introduction

In general, the principle of active noise and vibration attenuation does not change, whatever system it is applied to. This principle postulates that when opposite noise and vibration fields are equal to the original ones, but in "anti phase", the two sounds will cancel each other by "destructive interference".An anti-noise or-vibration is usually transmitted by a loudspeaker or a vibration transducer to the protected area in order to cancel there the existing unwanted noise/vibration. On the other hand, sounds to be heard, like speech, are subtracted from the canceled noise. These wanted sounds are reintroduced and remain at the end of the process undistorted within the domain of concern. Despite the fact that the use of destructive interference in acoustics was already understood in the last century (Rayleigh, 1877, # 264 and Tyndall, 1873, ch.1), the earliest known exploitation of it in ANC is a French patent by Coanda (1932). However, a more technical approach is linked to an invention published shortly later, in 1933, and patented during 1936 by Paul Lueg, a doctor of philosophy and medicine. Lueg outlines the principle: *The unwanted sound is picked up by one or more microphones, their electrical signal feed, to one or more loudspeakers so that the sound wave produced is in "phase opposition " to the primary unwanted sound and cancels it.* No physical argument was given explicitly in Lueg's patent. Later, the subject was developed into "active noise control" (ANC), which has now a precise theoretical and practical basis. Another early development is attributed to Bschorr (1969) for three patents about ANC, including noise elimination by an exact duplicate which is out of phase by 180°, and reduction of vibrating panels' noise radiation, Since then, the acoustics world everywhere has become flooded by publications and patents about active noise and vibration control. At present, the subject is still developing to a greater sophistication and efficacy.

Although the principle is simple, the feasibility of implementation depends on the size of source,its radiation distribution, and the ability to generate and control electronically spatial and time characteristics of the primary field. To adjust auxiliary sources to a maximum noise reduction and compensate for the time variation of noise sources and their environment, real-time adaptive electronic systems have to be used. Rapid

advances have recently brought these systems to some perfection, being cheaper and less clumsy as compared with the conventional passive solutions, in particular when the weight of the insulation is very important, and screening is impossible or too heavy.
Theoretically, the upper limit of ANC is the "zero option" defined by Doak (1988), which still necessitates effort and lengthy research, to yield a machine which does not radiate any noise. However, for "real life problems" a reasonable compromise and optimization may suffice in most cases.

Control algorithms

ANC is based on minimizing the acoustic field in a definite domain. The signals of the unwanted steady or time varying noise are collected by microphones. They are then processed by an adaptive electronic system that defines the canceling signals to be radiated into the relevant domain by secondary sources (loudspeakers and shakers for sound and vibration).
Another way is the feed-forward control obtained by a prior knowledge of the acoustic signal which is recorded by an upstream detection microphone.The feedback control in ANC was first suggested by Olson and May (1953). This strategy is linked to the basic theory of information as suggested by Shannon (1949) and Wiener (1949), and the theories of feedback and feed forward systems, including the use of interfaces with electrical filters, such as FIR and IIR.
M. Jessel (1967) made an important contribution to the theory of cancellation of sound wave radiated from a given source distribution by an array of Huygens sources (monopoles and dipoles) distributed over a closed surface surrounding the primary sources. Jessel, Mangiante and Canevet developed the method further under the name JMC. See Uosukainen (1990) and Mangiante (1990).
Now the interest moves towards more complicated algorithms including adaptivity (e.g. Kuo et al, 1994). A review about the subject is presented in the books Elliott and Nelson and by Tokhi and Leitch, both published during 1992. An additional paper with analytical clues about the subject was published by Elliott and Nelson (1993).
Here we note that active noise suppressing technologies, using electronic devices, can not be developed by one man's expertise, or at least require the following disciplines: Theoretical acoustics, vibration control techniques, electro-acoustics, signal processing and control engineering.

Early developments

While the principles of ANC were correctly described already by Paul Lueg, the claimed possibility of practical application turned out to be beyond the scope of even some sophisticated electronic applications today. Twenty years after Lueg's application for a patent, the successful experiments done by Olson and May (1953) with their electronic sound absorber, marked the beginning of development of compact ear defenders in which the ear cavity is actively maintained at conditions of silence. This solution, which was patented by Olson (1953), represents protection at the receiver (Wheeler 1981, and Jones and Smith 1983).In parallel, Bykhovskii (1949), Hawley and Simshauser (1953) developed ANC headsets as the most straightforward ANC. Later, the subject was developed commercially by Hesselmann (1974), Veit (1976) and others to ANC headsets, using small microphone-loudspeaker systems within earcups.

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Another local control strategy is ANC at the origin of the source (Bschorr 1970, 1971, 1973, Wurm 1974, Swinbanks 1976,1985, Wanke 1976, Chaplin 1981, 1984, 1986, Hori et al. 1984, Kallergis 1990, and Geddes 1991).
A large proportion of ANC development has been directed toward the control of noise in ducts, sources acting in free spaces, and sources within enclosures. Lueg's idea of ANC in ducts was developed later by Swinbanks (1972), Wanke (1972), Lawson-Tancred (1974), and the problem became more involved with electronics and design of electro-acoustic systems. Energetic issues and optimization were encountered in most of these works, and finally, the "time domain" aspect appeared to be of vital importance. Eghtesadi and Leventhall (1982) suggested a new approach to Active Noise Attenuation in ducts, using a monopole system. Up to that moment the current approach to active noise attenuation was based on two or three secondary sources. The monopole system had not been accepted due to lack of broad band attenuation and lack of stability. The new approach to the monoploe defined as "Chelsea monopole", offered for the first time a theoretical solution. This new concept uses the upstream radiation from the secondary source as a compensating signal which adds to the primary source radiation. With a proper signal processing technique,it can maintain a full range attenuation. Although some difficulties due to departure from the ideal characteristics by such sources were reduced by using one secondary source, its frequency response was still a major problem. Trinder and Nelson (1983) introduced the application of "acoustical virtual earth" to attenuation of broad band noise in an open ended duct with no flow. Their simple technique included a feedback loop to derive the sound pressure to a minimum at a microphone placed close to a loud-speaker in the duct wall. This produced reflected downstream traveling plane waves. The investigation of the loudspeaker's near field enabled identification of the optimum positioning of the microphone. The system is shown to be effective especially at the longitudinal duct resonances. The principal advantage of this technique is the simplicity of the control system which enables using low quality components, without the need for precision in design of the system phase response.
Attention was paid in the context of active control to noise in industry. A patent for reducing noise radiated by transformers, related more to environmental acoustics, was presented by Conover et al. (1957), while Brute de Remur (1960) developed ANC for a sound wave passing through an orifice in a baffle, which can be related to some degree to industrial noise. Self adaptive electronic echo cancellers were developed and patented separately during 1970 by Sondhi, and Kelly et al. This idea was applied in improving the acoustic impression in a room by cancellation of the cross-talk by Atal et al. (1966). Bschorr contributed to the early technology of ANC ideas about canceling propeller aircraft noise (1970) and other kinds of propellers' noise (1971), He suggested an anti-sound source which acts also as a sensor. Bschorr (1978).

Recent advances

The remarkable development in modern electronics has made active control schemes viable outside the laboratory. The ease with which difficult signal conditioning can be achieved with modern techniques has revolutionized the subject and stimulated a considerable research effort in recent years.
The most simple ANC which is the local active sound absorption, as was suggested by Olson and May, was followed by additional series of patents by Chaplin et al (1983), Swartz (1987), Peevers et al. (1985), Vermotel et al. (1988), Pass (1990), among

others. Also, Ziegler (1990) came forward with a patent for sound attenuation for a personal seat. Today, ANC headsets are available from various companies.

Reduction of noise in ducts by active control is being developed up to now. Hong et al. (1987) presented in 1984 a theory for the attenuation of tight-coupled attenuators, which constitutes a special form of the "Chelsea monopole" attenuator with almost zero microphone-loudspeaker spacing, along the direction of the duct axis. Practical and theoretical aspects of a tandem system is developed, using a two simple monopole attenuators cascade. The occurrence of different reflections from the duct walls is considered, and as a result sound radiation from a secondary source is not taken as plane wave. The tight coupled tandem attenuator can provide attenuation of 20 dB or more for more than three and a half octave bands from 30 to 330 Hz.

Curtis et al. (1987) applied the technique of minimization of acoustic potential energy to control a harmonic reverberate sound field in a finite length duct, and compared the method with two others. namely, The"acoustical virtual earth",where the added source is driven so as to maintain the sound pressure null in front of itself; The second one is the "absorbing termination", where the secondary source is driven so that no reflection occurs. In the minimization of acoustic energy, the secondary source strength is obtained by equating the differential of the energy with respect to the source strength to zero.One major result is that optimal termination achieves the best possible reduction of acoustic energy in the enclosure. At the expense of a non-causal control system, this condition produces half the acoustic energy of that resulting from a purely absorbing termination.In controlling periodic excitations optimal termination is practical, but even if the excitation can be previewed, the added complexity may not justify, in random excitations, the increased performance. In the last case, an absorbing termination can be most practical. "Acoustical virtual earth" does not achieve as satisfactory reductions in acoustic energy over a band of frequencies. A practical strategy which achieves a reduction in acoustic potential energy of a harmonic reverberate sound field is the minimization of the sum of the squares of pressures at several locations.

Munjal and Eriksson (1987) presented a one-dimensional standing-wave model of a linear active noise control system in a duct and a closed-form expression for the filter transfer function, which reveals the real role of the auxiliary source,and the importance of the distance between the input microphone and the auxiliary source. It has been stated that the success of the system obviously lies in correct prediction of this transfer function.

Scott et al. presented in 1989 a complete analytical model of active noise control in ducts, which allows for calculation of individual source power flows and downstream power flow as a function of source strengths and relative phase angles for finite size sources. The model for the finite size primary source in the plane of the duct cross section is evaluated for monople and dual secondary source arrangements, with results that show that the mechanism of ANC in a duct cannot be properly understood if the primary source is omitted during analysis. On the other hand, suppression of sound power flow down a duct, by using a single or dual secondary source combines suppression of primary source power output and absorption of primary source energy by the secondary sources. Hence, use of the word "cancellation" to describe the mechanism of ANC in ducts is incomplete and misleading, and the term ANA which includes the word "attenuation" instead of "cancellation" is often used.

The search for one-dimensional systems for quieting noise transmitted by duct has led to many patents, e.g. Ross (1981), Warnka (1984), Erikson (1987, 1989, 1991), Allie at al.(1988, 1989), Hamada et al.(1988), Takahashi et al.(1990), Dekker et al.(1990). Three-dimensional effects of ANC in ducts are taken into account more recently. Mangiante (1990), who introduced the JMC algorithm into active control of ducts, and the twin papers by Stell and Bernhard (1994), which deal with minimizing three performance criteria, namely, sound pressure at a set of selected points, potential energy in a selected volume in the wave guide and acoustic power in the downstream region of the wave-guide, and the research on the response of different arrangements of secondary systems in the duct. e.g. Kuo et al.(1994) should be mentioned in this context.

It is much more complicated to achieve ANC over spaces of more than one dimension, and mostly only a local improvement is achieved even when several secondary sources are used. A comprehensive review paper by Ffowcs-Williams (1984) gives a thorough analysis of the energetics of anti-sound. He explains there that acoustic energy and power are quadratic measures of the sound field and do not therefore add linearly. Precisely how the energy balance is modified when a source of sound competes with an anti-source is to be determined after the linear field quantities have been evaluated by superposition. The results are not always in accord with intuition and a whole variety of behaviors can occur in different cases. Most often it is found that anti-sound suppresses the power-producing ability of the primary source. Sometimes an anti-noise source withdraws and consumes from a primary source much more acoustic power than the source could produce or radiate in free space; the secondary source then acts as a "sound sucker". Sometimes the ANC can prevent sound energy from escaping into an exterior field just by trapping it in an internal reservoir of ever increasing noise.

In a large number of works, optimization techniques have been used to establish the maximum reduction in the controlled sound field.The technique essence is explained by Nelson et al.(1987). One selects the acoustical quantity of interest as a quadratic function of the strengths of the sources introduced to control the field. Thus one seeks a suitable quadratic measure (cost function) as the total power output from a given source distribution, the total acoustic energy in a region, or the sum of squared acoustic pressures at a number of positions in the field. Quantities such as these in terms of the secondary sources strength then permit identification of optimal secondary sources strengths which minimize the quadratic cost function considered. This lets unequivocal identification of how much the quantity of interest can be reduced by the action of the secondary sources, providing information for the engineer seeking to apply ANC. It enables an unambiguous evaluation of what can be achieved by acoustical consideration alone, before entering any examination of the means of achieving the control required.

Nelson et al. (1986) analyzed the free field of an optimized pair of monopole sources, with the power output as a cost function, and reached the following conclusions: In the low frequency limit, the secondary source strength is of the same order of magnitude and of opposite phase to that of the primary source, such that the combination of sources reduces to that of the primary source. However, as source separation is increased relative to the wavelength, it is demonstrated that in order to achieve optimal results, it is beneficial to reduce the strength of the secondary source relative to that of the primary one. In addition, the secondary source must for certain distances be in phase with the primary source to achieve the minimum possible output power. When the secondary source is many wavelengths apart from a primary source, it can do only little to influence the effective radiation impedance seen at the primary source. Under such circumstances it is better to avoid secondary sources. An important aspect of

these results is the time domain interpretation of the relationship between the primary and the secondary source strengths. In order to achieve optimal results, the secondary source must produce outputs "in anticipation" of the fluctuations in the primary source strength. The authors further analyze the maximum reduction in power output that can be obtained by using several point monopole sources to control the field of a number of primary monopole sources. It is shown in the low frequency limit that optimal sources arrangements do not necessarily reduce to classical types of inefficiently radiating source distributions. These results have been deduced from analysis in the frequency domain and it should be remembered that optimal results may only be achieved at the expense of secondary sources which act non-causally with respect to the primary sources (time domain). It is also shown that, for the numbers and arrangements of the secondary sources, significant reductions in power output may be obtained only if secondary sources are placed within a distance of one half wavelength apart from the primary source. However, it is possible to produce a substantial reduction in net sound power output with a relatively small number of secondary sources placed close to the primary source.
Another example of optimization of ANC is the work presented by Nelson et al. (1987) on the effect of sources within enclosures. They present an analysis of the effectiveness with which active methods can be used for producing global reduction in the pressure fluctuations amplitude of harmonically excited enclosed fields is presented. The total time-averaged acoustic potential energy is a measure of the most practical relevance in determining the global effectiveness of secondary sources of sound, since it leads naturally to a cost function based on the sum of the squared pressures sensed at a discrete number of locations. The first stage includes the case of a single primary source in a lightly damped rectangular enclosure when the frequency of sound is above Schroeder's cut-off frequency of the enclosure (high modal density). It is assumed that the sound field there can be expressed as a sum of the modal contributions. Substantial reductions in the acoustic potential energy cannot be produced if the secondary sources are separated from the primary source by a distance which is less the half wavelength at the frequency of interest. The use of active control in sound fields of low modal density is based on the same theoretical basis. In this case appreciable reductions in the overall potential acoustic energy are achieved by introduction of a small number of added sources spaced at a distance greater than half a wavelength from the primary source, provided the system is being excited close to a lightly damped acoustic resonance. The location of secondary sources which gives optimal reductions is at the maxima of the primary sound field, where the major contributing modes all share the same relative phases. Minimizing the sum of the squared pressures at a number of discrete sensor locations can provide a good approximation to minimizing the total time averaged acoustic potential energy, if the sensors are placed at the maxima of the primary sound field. Positioning a sensor at a corner of a rectangular enclosure of a low modal density field ensures detection of single dominant modes, and thus results in a near optimal reduction.
Nelson et al. (1990) presented classical time domain methods for determining the performance limits of ANC systems that are constrained to act causally. Previous work on the subject has mostly used frequency domain formulations in order to establish the physical limitations of active methods. While entirely adequate for prediction of the performance of ANC systems designed to deal with deterministic primary fields, they not necessarily can be applied when the primary excitation is stationary and random in nature. The application of frequency domain techniques often yield results for optimal

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control strategy that requires from the secondary sources to act non causally with respect to the primary sources. The first example considered is the minimization of the mean-squared acoustic pressure at a position in the field of a point monopole primary source by introduction of a point monopole, where the primary source radiates a stationary random signal. Active control of low frequency random sound in enclosure is then addressed. This theory is also used in a third example consisting a primary/secondary source pair that radiates in a free field.

Further progress in the investigation of actively generated quiet zones was lately made by David et al. (1994). Finally, we mention here the general statistical approach which seeks to quantify the performance of well known active control strategies in enclosures, specifying mean value and variance about the mean, as adopted by Joseph et al. (1994).

Echo cancellation in rooms was significant for "hands-free telephoning" - Berkley et al. (1974), Schiff (1987) and for removing howling instability, applying the room transfer function to the electronic compensating system - Christensen et al. (1978), Itoh (1986), Araseki et al (1987).

Generally, there are many patents related to ANC in enclosed spaces, since it is crucial in the aircraft and car industries, where weight, cost and size penalties should be minimal. Patents about such ANC are available especially for reducing peaks of resonances and canceling repetitive sounds, using room acoustics techniques and adaptive elements. Manufacturers of cars and aircrafts are interested in such developments and encourage patents on the subject - for example: Olson (1961), Clarion Co. (1977), Seifert (1982), Lorenzini (1984), Nelson et al. (1983), Peevers et al. (1985), Warnaka (1985), Swartz(1987), Kuipers (1987), Elliott et al. (1987), Salikudin et al. (1987), Fuller (1987), Elliott et al. (1988), Freymann (1989), Pass (1990), Eriksson et al. (1991), Elliott et al. (1992), Hanada et al., (1994),

Control algorithms were used already in active field control of auditoria and methods for handling loop gain to increase loudness, reverberance, spatial impression, etc. See, e.g. Kawakami et al.(1990). Maa (1994) has shown recently that the reverberant sound field in a room can be reduced as whole using an ANC system with both the pick-up microphone and the secondary loudspeaker in the corner region of the room.

Industrial applications involve most complicated sources.The unsteady burning in a turbulent flame is a process which produces both noise and associated unsteady light emission. Dines (1984) describes an interesting development in which quickly monitored light emission is used as a signal for the simultaneously produced noise of combustion. Other patents on the subject are by Roberts et al. (1987) & Margiarotty (1989). Improvement of flaws detection by reducing flow echoes was suggested by Huchens et al. (1989) and Gilbert (1989).

Berge et al. (1988) presented measurement results of ANC of two outdoor transformers' hum. An adaptive signal processor was used to generate 100 and 200 Hz tones in anti-phase with the transformer noise, at a single point some distance away from the transformer. The noise reduction obtained by the most suitable signal processing was in the range of 5-10 dB for equivalent and peak levels. The level reduction was up to 20 dB under certain conditions.

Applications have been reported by Elliott at al. (1988) on ANC of engine inside automobiles, and propeller induced cabin noise (1989).

The advance in microprocessors technology has made within reach many other applications in suppressing industrial and domestic machines noise within the spaces where they are located. For example, Nakanishi et al. (1991) helped Toshiba in

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offering a commercial ANC for a refrigerator and Hollowell et al. (1991) suggested an active vibration control system of an elevator.
In last years the subject influences also medicine, and Kroll et al. (1987) patented an ANC device to reduce the masking effect of lung sounds during diagnostics of cardiac sounds. Eliminating acoustic noise created by medical diagnosis devices was suggested by Friedlander (1994).
Recent advances in Active Control of Vibrations include a series of patents concerning the creation of secondary vibrations, e.g. Harper (1994), going deeper and deeper into technological details.

Trends

ANC becomes an efficient way of noise reduction, where conventional passive protection methods fail. This mainly happens when the noise to be suppressed is at low frequency and includes distinct frequencies, where passive means cannot be used and when the primary signals include both the relevant sound and the intruding noise. In such cases a new approach different from the passive one, is needed for those repetitive sounds. On the whole, their control by active means is straightforward and offers a practical solution in cases where either low frequency solid-borne or airborne periodic noise exists. (Clarion Co. 1976, Rose 1982,Crocker 1982, Seifert 1982, Lorenzini 1984, Chaplin 1978, 1979,1983, 1984, 1986, Taylor, 1987). The ANC is an efficient device concerning repetitive, low frequency noise signals, which characterize propellers. This kind of noise can penetrate the cabins of the aircraft passengers and cause there a considerable inconvenience. Researchers such as Warnaka 1985, Nelson and Elliott 1883, 1987, 1988, Sallikudin 1987, Fuller 1987, Hill 1991, Gardner and Ziegler 1992, were interested in adaptive structural ANC. Some of them suggested use of an error microphones array.
Consequently, many industries that are interested in the subject, develop and will develop in the future ANC units. Some of the leading companies involved in ANC are Bose, Nelson industries, Digisonix Division, ANVT, NCT and Contranoise. They have already elaborated definitely promising prototype devices, proving that the subject is ready for commercial use.
A relatively simple ANC unit is the "small zone silencer" and there are at least two categories for which its application has proven effective. One application is in the cavity between the ear and the ear piece in "earphone" type installations, and the other way is reduction of noise at the source. Algorithms for both local strategies are bound to further improve in the future.
ANC has deficiencies especially in time varying sound and vibration fields and when the domain has more than one dimension, and research workers try now to overcome those difficulties. See, for example, the algorithm for time varying signal prediction estimate maximize (EM) by Na Kam (1994).
A major development for preventing noise escaping from air-conditioning ducts and other kinds of wave guides occurs now and will go on including presentation of new theories and technologies.
The three dimensional problem is a most complicated one, and research reaches in this area a very high degree of sophistication. Yet the end cannot be seen, mainly as to the physical understanding and solution of such problems. An ANC solution that matches reality should consider fields created by real sources, such as combustion noises within

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interiors, and effects of high sound absorption by bodies and surfaces within the examined enclosure, where reflection of sound is scattered. This last problem of noise cancellation in rooms with sound absorbing surfaces was partly investigated by Rosenhouse and Saski (1995).
Structural vibration is often linear and occurs in a controllable frequency range, so that there is a natural application for these techniques. Such is the case with pulsate exhaust flow of internal combustion engines,large diesel generators,fans and exhaust units. One important line of progress is the application of active noise control in power plants. O'keefe (1994) shows that solutions by active noise control may improve also performance of machines, by eliminating some of the passive means, such as mufflers and absorbing materials. He also distinguishes between active devices for reduction of noise of few separate harmonics and broad band cancellation means. Both kinds of ANC units can function simultaneously.
The related field of Active Vibration Control is developing in parallel, as summarized by Soong (1990). It is based on algorithms built in a similar manner to those of the ANC, but the technology of vibrations cancellation is different from that of acoustic noise. It includes active tendon control, active mass dampers,aerodynamic appendages, hybrid active-passive systems etc. Finally, optimization procedures are used in order to get the best control system. In this context, superior algorithms are sought, such as the control algorithm with weighting matrix configuration, including reduction of the influence of time delay within stability regions, as suggested by Cheng and Tian (1993). The new research trends include the use of piezoelectric actuators, magnetic bearings, electro-rheological fluids, micro-processing and hydraulics on one hand and nonlinear motions control and active control of chaotic vibrations on the other hand. Applications include active control of vibrations of vehicle suspensions, active isolation against earthquakes etc.. There is a remarkable development in systems of active control of vibrations including typical components of control systems as sensors, signal processors, actuators error detectors, e.g., Macdonald et al. (1993)

Summary

To date, more than a hundred commercial companies develop simultaneously ANC systems. The trend is towards more sophisticated algorithms, in order to suppress complicated noise patterns, including solutions for three-dimensional spaces and time varying signals. There are today hundreds of patents and thousands of papers on the subject. Guicking (1988, 1991) described the growing interest in it, and since then the information has at least doubled in amount, with an increasing sophistication in theory and technical solutions to a variety of problems.

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