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AN OVERVIEW OF ACTIVE NOISE CONTROL

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ABSTRACT

Active noise control is commonly described as the cancellation of unwanted noise by the introduction of "anti noise". As early as 1933 Leug patented this concept and since the 1950's it has received a great deal of investigation. However it is only recently, as a result of significant advances in digital signal processing techniques, that Leug's concept has become an achievable and practical reality.

Active noise control has shown promise as a means of effectively minimising low frequency noise, with many examples of success in industrial and commercial applications. Subsequently, it has been heralded by some as the "cure-all" for every conceivable noise problem. However, while many institutions worldwide work towards broadening its horizons, the practicalities are still limited by the complexity of acoustic fields, cost, and difficulties experienced in the application of the technology.

This paper traces the history of active noise control, presents an overview of the general principles and technology, and reviews examples of both practical and impractical applications.

1. INTRODUCTION

Noise is an important consideration in both occupational and residential environments, with respect to comfort, communication, health and safety. Traditional methods of noise control incorporate "passive" techniques such as utilising sound absorbing and dampening materials, vibration isolators, or placing barriers between the noise source and observer. These methods however only prove successful at higher frequencies and while technically possible for lower frequencies they can become cumbersome, space intrusive and expensive.

With notable publications on the subject [1-6], the concept of introducing "anti noise", "cancelling noise" or "active noise control (ANC)", is becoming a viable complementary or alternative solution. While an old idea, technological advancements have recently allowed it to become a practical reality in an increasing number of applications. Notable

As the contents of this paper unfold, it will become apparent that, while active noise control does have limitations, it consistently has demonstrable success with low frequency tonal noise problems. The history and evolution of ANC is presented in the following paragraphs, together with outlines on physical mechanisms, the technology, its applications and future potential.

2. HISTORY AND EVOLUTION

The concept for active noise control (ANC) is not new, in fact it is over 60 years old. The earliest published documents on ANC were patent applications, one of which was submitted in 1933 by Paul Leug [7] . He proposed the basis of ANC, which is widely cited as the first publication of the concept. Leug suggested that a transducer in the path of a noise source could be utilised to generate a secondary, cancelling noise (figure 1).

Just a few weeks prior to Leug's application, Henri Coanda [7] also applied for a patent of similar goals. It too was based on the idea of phase inverted cancellation, but Coanda's concept of realising his objectives were technically incorrect. While Leug's proposition was more feasible, the technology did not exist for a practical realisation. Subsequently, there are no other recorded publications from either author and the idea died for two decades. .

It was resurrected by H.F Olsen in the mid 1950's [8], who not only published and applied for patents, but was the first to practically demonstrate that ANC was possible. He invented "an Electronic Sound Absorber" which consisted of a microphone immediately adjacent to a control loud speaker. "Negative feedback" absorbed incident sound. Technology was, however, still the limiting factor which prevented the invention from having any real practical or commercial value. Never-the-less, it was inspirational and generated renewed interest in the idea and its future potential.

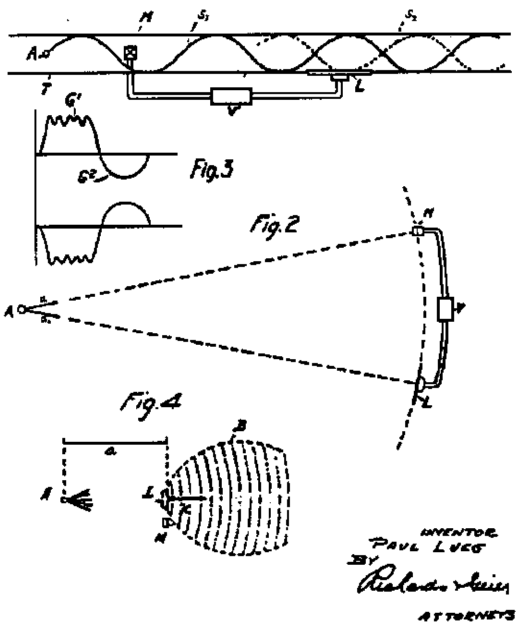

Figure 1. Leug's 1933 Patent Application

Commercially viable applications have occurred much more recently, due to the cost and processing time benefits of digital signal processors. As an example, papers were published on the idea of active noise control headsets in the 1950's, but these only became commercially available towards the end of the 1980's, over thirty years later.

The interest in ANC has continued to expand since the 1950's, as is evident by the exponentially increasing number of technical publications on the subject. Prior to the 1980's practical developments relied on digital technology made available via large and expensive laboratory computers. Since then, dedicated specialised digital signal processors at fractions of the cost and size have enabled ANC applications to prove successful outside the bounds of the laboratory.

ANC has evolved sporadically rather than with an even flowing progression, mainly because it relies on the synthesis of multiple disciplines (including acoustics, control, signal processing, electronics and computing).

Subsequently, rather than push the advancements in these specific fields, ANC has had to wait for technology to catch up and meet its demands.

3. THE PHYSICAL MECHANISMS OF ACTIVE NOISE CONTROL

Vibrating bodies [9] push and pull on the surrounding air, causing pressure variations and hence sound. These variations diverge from the source, through the transport fluid in waves of compressions and rarefaction's (voids) or maximums and minimums (figure 2).

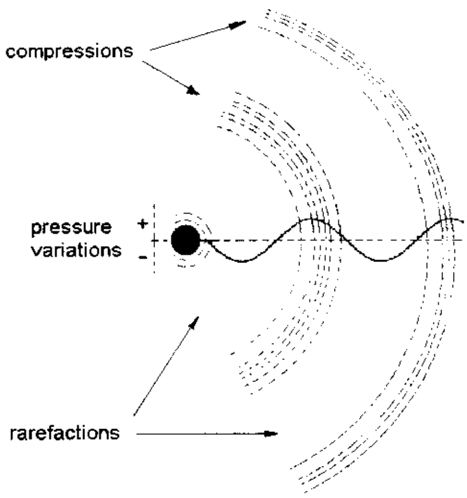

Figure 2. Transport of sound waves, from a vibrating body

The introduction of a secondary source, producing mirror imaged waves, of the same magnitude but 180' out of phase (noise source compressions synchronous with secondary source rarefactions and visa versa) will cancel out the pressure variations and hence sound (figure 3).

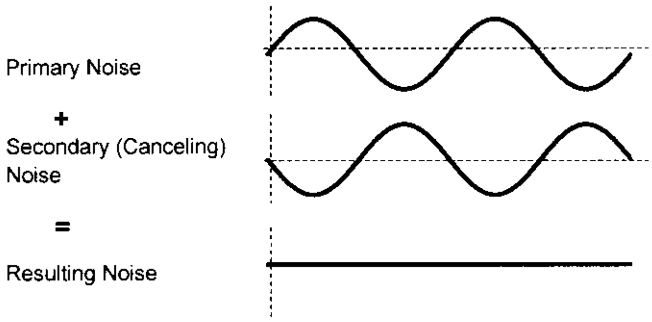

Figure 3. The principle of Active Noise Control

This concept of waves combining to cancel or reduce, is known as sound field modification by destructive wave interference. However while a secondary source wave may cancel a primary source wave, creating a "zone of silence" (or cone of silence for get smart devotees) it may be at the expense of generating additional noise elsewhere.

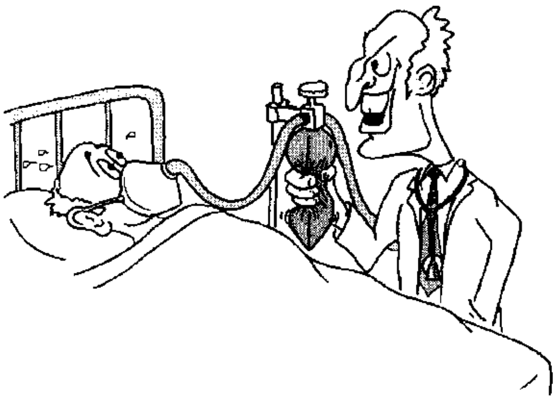

Figure 4. Modification of Impedance with Active Noise Control

A secondary source close to the primary source can also change the volume acoustic impedance with a detrimental effect on the efficiency of the primary noise source. This infers that the primary noise source would have to drive or vibrate harder to produce the same sound. But since noise sources (generally !) do not have a menacing intelligence the result is reduced noise. Consider the analogy of a patient breathing via an oxygen mask with the rubber bladder expanding and contracting on each breath. If the bladder is squeezed by hand when exhaling or pulled apart when inhaling, the patient must increase effort to maintain the same flow rate, or suffer a flow rate much lower if the effort is kept the same. For this mechanism to work, the secondary source must be large enough and/or located close enough to the primary source to be capable of affecting the impedance presented to it by the acoustic field.

Another mechanism utilises the sound energy of the primary noise source to drive the secondary, or cancelling source, resulting in sound absorption by the cancelling field. However, there is never sufficient energy to drive the secondary source, due to the very low electro-acoustic efficiency of most noise sources. Consequently, amplifiers are utilised to assist the efforts of the secondary source.

4. ACTIVE NOISE CONTROL SYSTEMS

An active noise control system [8] must consist of a transducer to measure the sound pressure, a signal processor to generate the control signal and a control source to excite the acoustic field. Multiple transducers and/or control sources can be used in modem systems providing a more globalised field of control.

The choice of sensors and control sources depends on the primary noise source, physical environment and primary sound transmission paths. Noise may be airborne (travels through the air) or structure borne (travels through, and is subsequently regenerated by the structure). For predominantly airborne noise, microphones and electrodynamic loudspeakers are the common option, but the choice can become more complex when structure borne noise is a significant contributor. While microphones and loudspeakers may still prove to be of benefit, sensors and actuators attached to the transmitting structure may also be used. These sensors directly measure the structural vibration, while the actuators modify the vibration response of the structure. Actuators may be hydraulic rams, electrodynamic shakers or piezoelectric patches that deform when charged. A piezoelectric patch bonded to the structure may also be utilised as a sensor, as it generates a charge when distorted by structural deformation. Other typical structural sensors include strain gauges and accelerometers.

In enclosed volumes, standing waves are generated producing high (and low) sound levels at fixed discrete locations and frequencies. Therefore, when the sensor is a traditional microphone, placement becomes all important. A wrong location might see the microphone "blind" to certain frequencies. By utilising combinations of microphones precisely and closely spaced with respect to wavelength, the energy density of the acoustic field may be measured and utilised for control. The energy density is the summation of potential energy (pressure, directly from the microphone) with kinetic energy (particle velocity, proportional to the acoustic pressure gradient). Utilising Newton's idea of energy conservation, the combined energy is a much more consistent quantity throughout the volume.

The signal that drives the control source is generated electronically by a digital signal processor, utilising the input from the sensing transducer(s). Steady state conditions provide an ideal environment for control but in practice variations in the acoustic field and primary source almost always occur. Controllers therefore need to "self -tune" or be adaptive to changes in the system being controlled. The component configuration, use and principle of operation of ANC systems may be divided into two broad categories:

Adaptive feedforward controllers and

Feedback controllers

Adaptive feedforward controller receive data from a transducer (reference sensor), to anticipate the noise entering the sound field. This could be a tachometer signal, if periodic engine or fan noise was of issue, or an "upstream" microphone. A control algorithm, filter and amplifier provide output to a control source (loudspeaker or actuator) in time to cancel the incoming wave. The controller, via a second (error) transducer measures the success of cancellation and fine tunes (adapts) the filter accordingly, to minimise the square of the error signal (Least Mean Square, LMS). Figure 4 demonstrates the principle of a feedforward controller with one noise source, but in cases where there are more, it is necessary to take a reference from each and use a multiple input controller.

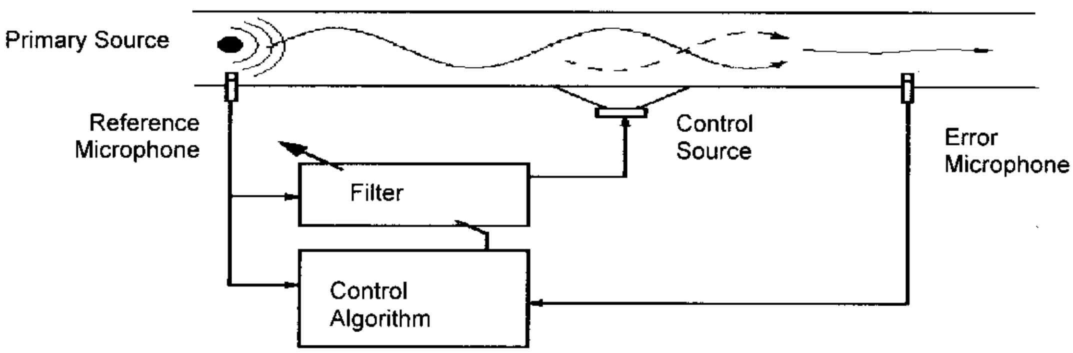

Figure 5. Feedforward Control

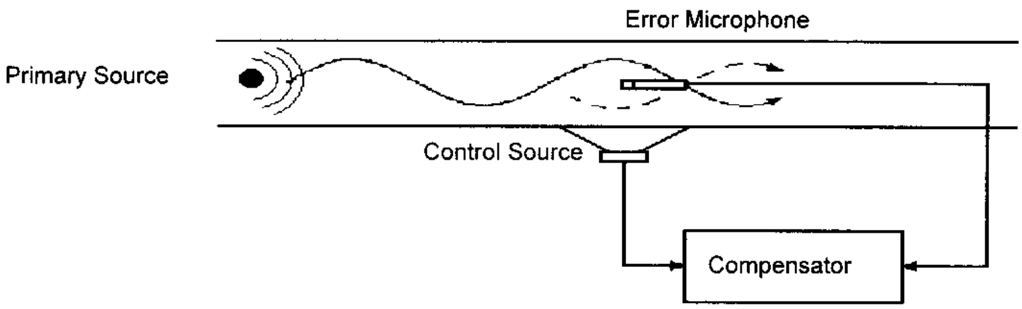

Figure 6. Feedback Control

Feedback controllers (figure 6), somewhat less common, operate quite differently, with no requirement for predicting the incoming disturbance. Instead, they focus on the error signal, with a closed loop "tuning" the overall response and output of the controller. Based on a high gain negative loop feedback, feedback controllers of significant performance can be prone to instability, and are therefore limited in their applications

5. TYPES OF NOISE

Noise, or waves may be divided into a number of categories including; periodic, random and transient.

Periodic waves are waves that consist of a repeating pattern, usually a complex combination of sinusoidal tones. Their inherent predictability makes them the most likely candidate for successful feedforward ANC. The degree of success in controlling this sort of noise is a factor of environment, transmission path, wave complexity (or modal density) and the upper frequency of interest. The frequency must be low enough (usually below 500Hz) to provide sufficient time for the system to react and adapt to control the noise. Utilising ANC above 500Hz will start to develop system and physical limitations and may result in costs which would exceed more practical passive control methods. Noise problems that consist of tones spread over a wide audio frequency range may best be approached by a combination of active and passive control methods.

Random noise, by definition non-repeating and therefore unpredictable by nature, is often tackled using feedback control. However, feedforward control of random noise can be successful in duct systems, where the incoming signal can be sensed upstream, in sufficient time for the controller to generate and output a cancelling signal to the control source.

With respect to transient noise, unless the mechanism producing the noise can be utilised to predict its occurrence, there is a surprise element, which will not be countered by the most intelligent of controllers. Transients also excite broad bands of noise and are generally (with a few exceptions) poor candidates for a basic ANC system.

6. APPLICATIONS

Active headsets [10] demonstrate success with ANC and are commercially available, not only from specialist stores but also high street electronic retail outlets. In the absence of a well defined reference signal, the active headset for generic applications will utilise feedback control. However headsets may be designed to integrate with a specific system, utilise its reference signal, and operate via a feedforward system. Used in high noise vehicular cabins (such as light aircraft or tractors) they generally allow communication (or music) via an intercom input to the controller. Models currently available are no larger than a personal stereo, but while they offer distinct noise reduction benefits, it is at the expense of physical freedom and comfort reduced by the necessity of wearing them.

Stereo speakers in cars may also be utilised as control sources in a feedforward ANC system to minimise both engine and road generated cabin noise [11]. While road noise reductions of up to 7dB (below 200Hz) have been reported, these are limited by the difficulty in obtaining a suitable reference signal.

Success with ANC in passenger aircraft has been demonstrated by fitting control and error sensors into the head rests of seats. While successful when heads are kept within the locally controlled zone, varying amplitudes of attenuation will be realised by movement, especially when leaving a seat. The goal of a more globalised control is currently an area of interest for numerous research and industrial establishments.

Utilising the rotational speed as a reference, the tonal noise produced by a fan at the blade pass frequency in a duct can be controlled with a feedforward system [12]. While the area of best noise reduction is immediately adjacent to the error sensors, success is also evident globally in the far field.

Cavitational or fluid borne noise **in** pumps, have been shown to benefit from feedback control. George Piper [13] reports on a discernible reduction of fluid borne noise, in a magnetic bearing pump.

Power Transformers notably hum and are very much a tonal problem best approached with a feedforward system. Often situated outside and open to the elements, an alternative control source to the traditional loud speaker is a curved panel excited by piezoelectric patches. These have demonstrated up to 15dB of noise reduction over a narrow angular arc, but success is more difficult as this arc approaches the full 360°.

Industrial presses or punches can generate high impulsive or transient noises which as previously stated can be difficult to control. However such automated machines generating the same repeated transient may operate a switch, prior to impact, triggering a control source to emit a cancelling transient pulse.

While not strictly an acoustic issue but on the subject of a primary source driving the secondary; GEC [10] have reported success in minimising vibration in printed circuit boards by utilising the primary vibration. Piezo electric patches attached to the boards generate electrical energy when deformed. Mechanical energy absorbed by the patches is ultimately dissipated as heat.

However, there are also the many applications that cannot be improved by ANC. Environmental or multiple source noise in either very large enclosures (such as factories) or open areas is not globally controllable within the realms of practicality. The multiple source, broad band, multiple transmission path and sound diversity all contribute towards a physically uncontrollable situation. Similarly, the sporadic noise experienced at home due to either noisy neighbours, passing traffic, trains, aircraft or merely the elements is also uncontrollable.

7. THE FUTURE OF ANC

While there are recognised limitations in what ANC can and can not do, it is still a youthful science full of windows of opportunity. ANC will continue to advance in the applications already demonstrating success, with a focus on higher levels of sound attenuation and more globalised control. It is also likely that many parallels will be drawn between applications not previously considered and those currently demonstrating success. For example, while significant advancements are being made in automobile or commercial passenger aircraft ANC, light aircraft cabin noise has only recently become targeted as a candidate worth pursuing. Technology will also improve with processors becoming smaller, cheaper and faster. The benefits of speed however will not lead towards the control of higher frequencies (better dealt with passively) but more reliable, stable and successful controllers. Price reductions, as well as realisation of the benefits, will lead towards wider use and commercialisation.

Ultimately ANC will become as prevalent as a cars electronic ignition or catalytic converter. In the automotive industry it will be marketed as an optional extra like air conditioning or central locking.

ANC will not be the "cure all" to every conceivable noise problem and is still very much in a period of R &D, but it will see future widespread use in many diverse (but appropriate) applications.

Its use will benefit improved communication, it will reduce stress, fatigue and intolerance to otherwise noisy environments, contributing to more comfortable and safer occupational or recreational conditions.

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