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Physical and biological aspects in active sound and vibration control

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Abstract

Sound is a physical phenomenon that involves mechanical waves. It exists in nature and can also be generated by man made devices. Generation of intentional sound and/or vibration fields in order to change existing sound and vibration fields is Active Sound and Vibration Control (ASVC). Active Noise and Vibration Control (ANVC) is a part of ASVC, and it means attenuation of undesired sound and noise. ANVC embraces reduction of noise and vibration in many applications, as these in the car and aircraft industries, structures and audio engineering among others. On the other hand, ASVC has many disciplines other than noise reduction, where mechanical waves couple with others or with different kinds of waves (electrical, optical, magnetic etc.) or with chemical processes. ASVC generation involves not only Hi-Tech technologies, but can be generated by other means. In nature, ASVC may it become a life or death question (in prey hunting for example). The ASVC in nature stimulates bio-mimics ideas for radar and sonar systems design, robotics, electro acoustic technologies (e.g. three-dimensional direction location and other applications). Being interdisciplinary, ASVC necessitates, for its further development, basic knowledge in physics, biology, theoretical acoustics, electro acoustics, control engineering and electrical engineering to help solve or study problems of specified characteristics. Following all the possibilities mentioned above, a new generalized concept of ASVC (or ANVC in its restricted form) is presented here.

1 Introduction and an extended definition of active sound (noise) and vibration control

The books about ANVC up to now (all published during the years 1992-2001 (Nelson and Elliott [30], Tokhi and Leitch [38], Fuller, Elliott and Nelson [16], Hansen and Snyder [17], Kuo and Morgan [25], Comte-Bellot [7], Snyder [35], Elliott [10], Hansen [18] and chapters in books and conferences) emphasize noise and vibration cancellation by generating an anti-phased sound field that is the replica of the intruding sound field, using secondary sources. Usually these sources are a part of an electro-acoustic system that includes sensors, a control unit and sound or vibration radiators. Audio systems (surround systems and so on) are exceptional since they are supposed to improve the sound field by using Active Sound Control (ASC) and not to cancel it. Yet, the traditional ANVC misses a much broader definition as given in Rosenhouse, 2001: **Active Sound (or noise as a sub group) and Vibration Control (ASVC) includes any type of generation of secondary acoustic fields in order to change intentionally the primary acoustic field in favour of acoustic or other needs.**

This definition expands the frame of ANVC in a way that allows for an overwhelming number of applications, and goes far beyond the basic definition of Lueg in 1933.

2 ASVC for physics and chemistry

ASVC may couple with other areas of physics in a useful way. Examples are:

- Absorption and scattering of sound by sound (non linear waves and vortices).
- Thermodynamics of reduction of combustion noise by sound.
- Sound scattering and absorption caused by turbulence.
- Optoacoustics (OA) scatters light by sound.
- Sonoluminescence, where light is generated by sound.
- Acoustic levitation.
- De agglomeration aided by ultrasound.
- Agglomeration aided by sound radiation by pulsating cavity.

Many renowned researchers brought results about sound fields interactions and established formulation and principles that allow for ASVC design for all these topics. See chapters 2 and 3 in Rosenhouse [33] for details and references.

3 Noise cancellation

3.1 A new principle

A new principle that extends the scope of ANVC and ASVC results by combining Huygens' principle, the concept of locality that resembles the dynamic Saint-Venant's principle in mechanics and wave superposition (Rosenhouse [33]). It states that if there is any acoustic source, that generates a

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propagating linear wave front, the source can be replaced by a suitable equivalent discrete system of sources over a selected wave front. This front is defined as the sources' surface (e.g., a sphere within the source domain). Each source in this array of acoustic sources radiates a wavelet. After a short time and at a distance from the source surface, which is large enough, a new wave front, which approximates that radiated by the original source, will be superimposed by the wavelets of the discrete equivalent system.

For the purpose of cancellation of the original field, a destructive interference at prescribed control points, can be obtained by inversion of polarity of the collocated replacement (or secondary) sources that belong to the equivalent system. An electronically supported optimisation procedure can be added for adaptive modification of the secondary sources.

It is assumed that in ANVC the far field magnitude as a whole will change without noticeable effect of the discretization under limiting conditions (such as frequency and the distance between the secondary sources). Under similar conditions as those where Saint Venant's principle is satisfied in solid bodies, the local effect of the discretization tends to disappear as the distance from the equivalent system and the original source increases.

In spite of the fact that in practice this rule exists, rigorous mathematics is needed for the definition of the maximum permitted distance between the discretization points and the frequency domain limits in each specific problem. It means conditions that are necessary in order to satisfy this acoustic principle.

A partial "coverage" of the wave front by the equivalent system leads to a partial equivalence in the sound field. E.g., more attenuation in a certain direction from the source is obtained if the system is optimised and the equivalent system is denser in this direction. This leads to a local "quiet zone"; while in other places acoustic intensity might be increased. Guo, Pan and Bao [12] and Guo and Pan [13] have shown a simple case of quiet zone. Yet, the general rule is much wider, and suits various configurations of main and secondary sources, and boundary conditions in the domain.

3.2 Active devices

Commonly, ANVC sensors sense the disturbing field emitted by the primary sources and transmit the information as data to be processed by the ANVC or ASVC control unit. The control unit uses generally a mathematical algorithm for the electrical signal processing. The processed information is then delivered to actuators that radiate in turn an anti-disturbance acoustic field. In order to achieve good results, this process must be within an allowed error margin.

In ANVC, the signals of the undesired steady or time varying, acoustic or vibrational noise are collected by microphones or by vibration sensors and transmitted to the computing unit by a linking interface. They are then digitally processed by an adaptive control that calculates the cancelling signals to be radiated by secondary or auxiliary sources (such as loudspeakers for sound and shakers or ceramic actuators for vibration) into the control region. At this step,

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an interface changes the digital results into analogue output. The superposed field is measured and the error is feedback for correction by the control system. ANVC systems may in certain case lead to a poor solution, especially by violating the allowed limit of error in phase and amplitude of the intentional field. This situation happens mainly in time varying sound fields, very high amplitude waves or non-linear fields and when the domain has more than one dimension. It is also difficult or even impossible to apply ANC against high audible frequency waves and a very dense array of cancellers is needed under such circumstances. The same situation applies also to vibrations that are to be reduced. In this context, causality becomes an important factor in designing ANVC algorithms. It means the ability to sample the unwanted noise by a time interval earlier than the radiation of the anti-noise so as to enable data processing. Theories of feedback, feedforward and mixed systems, using devices with electrical filters, such as Finite Impulse Response (FIR) and Infinite Impulse Response (IIR) and additional adaptive means in complicated control interfaces already exist. Interest has been moving now towards more complicated algorithms, including MIMO feedforward control with a multi-rate controller.
In cases of significant non-linear effects generic non-linear filter structures, such as polynomial or neural network filters can be used.

3.3 The control part in active sound and vibration control

ANVC definitely belongs to the area of control systems engineering and signal processing, and it has usually to remove unwanted acoustic disturbances and to improve quality of heard sound and eliminate damaging vibrations. Good results can be obtained only by minimizing the errors by using a chosen cost function. To reach this goal it is necessary to construct proper control units (using combinations of feedback, feedforward and hybrid components, among others) and develop learning capabilities. The resulting control algorithms are designed to bring existing inputs as close as necessary to the wanted ones.

A design failure for example, due to lack of a comprehensive physical understanding of the problem, may lead to negative effects, such as losing the stability of the process that causes the collapse of the acoustic outputs. Hence, a physical insight to the control system is of major importance.

3.4 Passive/active and semi active control devices

A most effective way of ANVC is its coupling with passive isolation means. Under such schemes the active control plays a corrective role, while the passive isolator is on charge of the heavy duty of main amplitude reduction. This hybrid isolator that is based on active/passive coupling, is used typically against strong excitations under conditions of uncertainty. Examples are building isolation against the non-deterministic vibration during earthquakes suspension systems and machinery soft mounts against resonant structural dynamics.

The semi-active control is based on changing the acoustic response of a system by electrically controlling its shape and properties. E.g. the design of moving cores for the cells' silencer (Rosenhouse, Findling [32]). The motion of the core adjusts the lengths of the cells in accordance with the spectrum to be attenuated. An a-priori adaptive process attains an optimised silencer. Adjustments can be made later continuously by the electrical system with the engine working. This system can be combined with a conventional ANC unit.

4 Patents and technologies

The existing solutions and patents that apply ANVC include active ear muffs, elastic-active combination of mountings, ANC in ducts, control of panels vibrations, active sound absorbing walls, acoustics in 3-D spaces (in airplanes, cars and buildings), hybrid control of machine vibrations, AVC of high rise buildings (what happens if the system does not work during an earthquake or is damaged during a catastrophe?), application of piezoelectric materials for active vibration of the wings of light weight airplanes, special uses (in medicine, home appliances and so on), development of dedicated control algorithms, electro acoustic devices, vibration transducers, etc.

5 Simulation

The aim of the ANVC is to obtain an optimised secondary acoustic field that in the most common devices cancels an unwanted noise in a certain domain. For that purpose modelling of real systems can be useful, giving hints about the results. Existing mathematical formulation helps in optimising the sought solutions. But, in complicated domains, the analytical approach becomes extremely difficult (or even practically impossible). Rosenhouse [33] suggests using simulation based on Virtual Reality (VR) methods for approaching the optimised field by changing the simulated properties and the locations of the secondary sources on the computer screen. While the simulation uses often one frequency component, the ANVC system functions usually in the time domain, using incremental adaptive changes. This approach can apply also in ASVC.

6 Active control in biology

There are three major ingredients in ANVC, namely, the sound source, control system and sensors. Some animals like bats and dolphins have all of them, and some of them, like owls, have only a part of them. All these mechanisms can stimulate innovations in ANVC and ASVC, and part of them, like the active skin, is already used. Here, a short review of such mechanisms is given:

6.1 Localisation

Localisation is the ability to determine the direction where a sound source is located. Human beings have this ability by using two ears that are apart from each other. A demonstration of a phantom source by two loudspeakers is given

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in Rosenhouse ([33], pp 147-148), where a directional illusion was achieved by generating different amplitude for each loudspeaker.

An animal that is specialized 3-D localisation is the barn owl (Knudsen and Konishi [21], Konishi [23], Day [9], Knudsen [22], Linkenhoker and Knudsen [24] among others). For that reason, research workers tried to find the mechanisms behind this ability. The ability of the owl to localize sound sources in a 3-D space depends on the location of its ears and the signal processing by the owl's brain. Several models explain the way the brain combines acoustic signals from the two ears into a unified spatial perception

Experimental evidence with barn owls, chicken (Carr and Konishi, [6], etc.) and cats (Smith, Joris and Yin [34], etc.), has shown these delay lines that are correlated with interaural time difference (ITD) processing. On the other hand, Brand et al. [5] have found that the Mongolian gerbil's neuronal response to ITDs is followed by fast inhibitory inputs in the brain.

While the owl and other big animals can find directivity towards the source due to the spacing between the ears, this procedure does not suffice for small animals. E.g., the two ears of the parasitoid fly Ormia ochracea are not far enough to sense interaural difference, since in this case the time difference is of the order of magnitude of 1 μs. Hence, such a mechanism was developed by evolution in a way that increases this difference in the sound signals before reaching the auditory receptor cells (Michelsen [26]). In this process each ear responds to the combination of pressures that arrives at each side of the body. This way, the ear that is closer to the source (ipsilateral) responds to higher pressure than the far ear (contralateral) – e.g. Fletcher et al. [14]. Miles et al. [27] have shown that since the ears of the Ormia ochracea are very close and the are joined by a cuticular structure, they are mechanically coupled, which in turn magnifies the interaural differences. They modelled this concept of localization analytically, and the results were supported by measurements. .

6.2 Echolocation

Bats, which are nocturnal mammals, possess at least in part, a unique active acoustic control system that "sees in the dark" using "acoustic radar" for prey searching, identification, pursuit and capture (see Rosenhouse [33], section 2.3.4.7, under the title of "moving sources"). The revealed interest was strengthened recent years also because of the possibility of adopting to robotics a convenient and cheap acoustic echo-location system for ranging and definition of direction and size of objects - Kuc and Barshan [3].

Not less fascinating than the bat is the dolphin, who lives in water rather than air, and is exposed to much more reverberation and background noise. They are caused also by the acoustic source of the sonar due to echoes reflected and scattered by objects and inhomogenieties within the water. This type of sound field is very problematic and inferring since the reverberant sound has a spectrum that is similar to that of the source itself, and it is also proportional in amplitude. This unchangeable signal to noise ratio limits the target detection sensitivity. See Au [1,2] for the reverberation effect on the sonar equation.

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6.3 Sensitivity to vibrations in nature

Crocodilians have organs dome pressure receptors (DPRs) on their faces that are connected to the hypertrophied nerve system, and are capable of detecting very small disruptions in the surface of the surrounding water, caused by location of their prey. The faces of alligators (Alligator mississippiensis) are covered with small pigmented domes, outside and inside the mouth. Experiments in full darkness with half submerged alligators revealed that they are sensitive to single water droplets, with their hearing organs shut. Soares [36] investigated this effect in crocodilians and lizards and found that only animals that are semi-aquatic show the same pattern of vibration perception as that of the crocodilians.

Well known is the vibratory sense of spiders, where their eight legs interact in orientation (Hergenroder and Barth [19], Barth, [4]). Also, other kinds of animals communicate by vibrations (e.g. Kalmring [20]), and for example, the treehopper (Umbonia crassicornis) communicates by using bending waves that propagate along plant stems (Miles et al. [28]).

6.4 Blocking noise penetration into the hearing organs

The fly Drosophila melanogaster has very small hearing organs each of which consists of 3 antennal segments and a feather-like arista. These parts constitute together the sound receiver. When a desired sound is heard, the arista rotates one of the antennas and penetrates a hook into the second antenna (the internal one) and stretches the auditory receptors. At such conditions the auditory receptors can function and enable hearing. Otherwise the Drosophila melanogaster hearing is prevented. Goepfert and Robert [12] give a more detailed description.

Other kinds of animals can also inhibit their own hearing, like humans (Creutzfeldt et al. [8]), bats (Suga et al. [37]) and frogs (Narins [29]). A special example is that of the singing cricket (Gryllus bimaculatus). Its strong voice could deafen temporarily its hearing. Poulet and Hedwig [31] investigated male crickets that produce loud mating, courtship and territorial sounds. The auditory responsiveness of the Ω neuron of the central nervous system (CNS) was normal. However, when the cricket was singing by wing stridulation, the Ω neuron did not generate spikes, but inhibitory synaptic potentials appeared with every wing stroke, correlated with the inhibition.

These mechanisms resemble the functioning of the limiter in audio systems.

6.5 The skin control

The basic motion program for voluntary movement in an arm is embedded within the neural circuity of the arm itself. A starting point in this area is search of the control of the octopus arm, which has a huge number of degrees of freedom (in any direction) monitored by commands that activate forces to reach a given target. This motion has optimal trajectories. The arm maneuverability is controlled by a peripheral nervous system, along which about $5x10^7$ neurons are distributed (for each of the 8 arms, which is much more totally than the $150x10^7$ for the whole central brain) and about $4x10^5$ of which are motor neurons that locally stimulate and control the muscles of the arm, independently of external circumstances. Generally, the procedure lets the neuronal networks activation with exact details in space and time, while the central system at the brain sends global activation commands, which makes the whole functioning more efficient and simple.

The active noise control by wall and duct surfaces introduces a mechanism of artificial active skin. A different but related example is the attempt by Fuller and Carneal [15] to use a design approach, which is defined by the authors as the biologically inspired control approach to distributed elastic systems, using multiple piezoelectric actuators.

6.6 Human beings

Communication by speech and hearing can be considered by definition as active sound control. When two people speak with each other, the "loudspeaker" is the mouth, the ears are "microphones" and the brain serves as the "active controller". Obviously, the response of the listener is the result of this ASC process

In certain cases tinnitus can be partly relieved by using artificial sounds as active cure. E.g. shower and shaving electrical razor noise. The effectiveness of these means depends on the patient's condition.

7 Summary

The general progress in electronics and control algorithms advanced the construction of ANVC control units, actuators and sensors, and modern DSP improves the ability of ANVC to produce an almost real time control of undesired signals of very complicated forms. A new definition of sound control that is defined as ASVC expands the idea of active cancellation of sound to any changes in acoustics and also generally in physics. However, this does not suffice, and physical argumentation is not only necessary but can also contribute to new physical, medical, psycho acoustic ASVC ideas and devices.
Technological ideas for ASVC can be adopted from nature, as can be concluded from the examples given here.

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