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Active Control of Sound and Vibration History – Fundamentals – State of the Art

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Abstract. In a narrow sense, coherent active control of sound and vibration is the cancellation or (less often) enhancement by superposition of an antiphase or in-phase additional signal, usually from an external source of sound or vibration. The historical development of the technologies are outlined, the fundamentals under aspects of physics, signal processing and algorithms are treated, and the current states of research and applications are reviewed, more or less systematically sorted. Related fields such as adaptive optics, active flow control, and control of nonlinear dynamic systems are also included. Active control of sound and vibration in a wider sense, the incoherent superposition, aimed at sound power enhancement etc., is not considered in this survey.

1 Introduction

The concept of cancelling unwanted sound or vibrations by superimposing a compensation signal exactly in antiphase is not new. In acoustics, most of the early publications in this field are patent applications, showing that technical applications have been considered possible. However, for a long time experiments were nothing more than laboratory demonstrations which were smiled at as curiosities, far from reality. Only modern electronics made technical applications feasible.

The situation was different with the compensation of low-frequency mechanical vibrations; these techniques were used in practise at a very early stage. In the following, an overview is given of the historical development, technical realisations, and present research activities.

2 Active noise control (ANC)

2.1 Early investigations

The first experiments on the superposition of sound fields were presumably made in 1878 by Lord Rayleigh [1]. He describes under the heading “Points of Silence” how he scanned, with his ear, the interference field produced by two electromagnetically synchronised tuning forks, and that he found maxima and minima of loudness. Although it can be assumed that these experiments should only prove that coherent sound fields can interfere in the same way as do optical fields (which was known since the days of Thomas Young), patent applications by Coanda [2, 3] and Lueg [4] were aimed at possible noise reduction – however only in Lueg's proposal in a physically realistic way. Lueg's German and especially the related US application [5] with an additional sheet of drawings are, therefore, considered rightly as the first written documents on active control of sound.

Lueg already proposed the usage of electroacoustic components, but the first laboratory experiments were documented by Olson 1953 [6] and 1956 [7], who also listed far-sighted prospective applications. Technical applications were not possible at that time because of the clumsy electronic vacuum tube equipment, lacking sufficient versatility. Also, our ears present a problem, namely the nearly logarithmic dependence of the perceived loudness on the sound pressure. For example, a sound level reduction by 20 dB requires an amplitude precision of the compensation signal within 1 dB and a phase precision within 6 degrees of the nominal values – for all frequency components of the noise signal. These demands, together with the requirement of temporal stability, have impeded for a long time the technical use of coherent-active compensation systems (also termed *anti-sound*) until in recent years digital adaptive filters proved to be the appropriate tool.

2.2 The energy objection

In the context of the active cancellation of sound fields a question often posed is "Where does the energy go?" With the seemingly convincing argument that the primary field energy can only be enhanced by adding secondary sound sources, the concept of active noise control (ANC) is principally questionable [8]. The objection is correct if the cancellation is achieved by interference only; a local cancellation leads to doubling of the sound pressure elsewhere. But a more detailed consideration reveals that the secondary sources can, properly placed and driven, absorb the primary energy. In other situations, the sources interact such that the radiation impedance is influenced and thereby the sound production reduced. This will be elucidated in the following sections.

2.3 The JMC theory

M. Jessel and his coworkers G. Mangiante and G. Canévet have developed a theory which has become known, after their initials, as the *JMC theory.* They have treated the problem sketched in Fig. 1 (e. g., [9]). Sound sources Q are located within a volume V with surface S. Along S, secondary sources shall be arranged such that they compensate the sound field radiated to the outside, but do not alter the field within V. This is possible according to Huygens's principle: substitute sources q continuously distributed along S can create the same sound field in the outside as the primary sources Q. With reversed poling, they produce a field which is in antiphase to the original one. Assuming that such reversed (and acoustically transparent) substitute sources operate together with Q, the sound fields in the outside cancel each other.

If the cancellation sources are acoustic monopoles they radiate not only to the outside but also into V, creating standing waves and enhancing the sound energy in

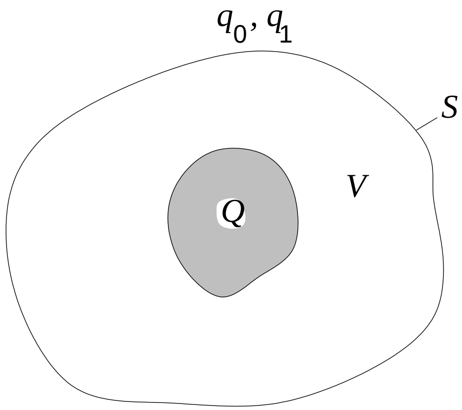

Figure 1. The Jessel–Mangiante–Canévet (JMC) theory.

V. The inward radiation can be prevented by combining monopoles q_0 along S with dipoles q_1 so that the primary field in V is not altered. As to the energy, the *tripoles* formed by the q_0 and q_1 (directional radiators with cardioid characteristic) absorb, along S, the sound coming from Q. They serve as perfectly matched absorbers with an acoustic input impedance equal to the characteristic impedance of the medium.

With the same argument, it follows that a source-free region V can be shielded actively against sound influx from the outside by arranging appropriate compensation sources along the surface S of V. Monopole distributions along S reflect, tripoles absorb the incident sound.

For a given surface S and primary source distribution $Q(r)$, where r is the position vector, the substitution sources $q_0(r)$ and $q_1(r)$ can be calculated from the Helmholtz-Huygens integral equation which links the sound field in a region to the sound pressure and its gradient along the surface [10].

For practical applications, the theoretically required continuous source distribution has to be replaced by discrete sources. Their minimal surface density follows from their absorption cross section $A = \lambda^2/4\pi$ [11] and the smallest sound wavelength λ for which the system shall be effective. This concept has been verified in computer simulations [12] and experimentally in an anechoic room [13]. A practical application is noise shielding of large open-air power transformers by an array of loudspeakers to save the people living in the surroundings from the annoying hum [14]. It was also reported that cattle grazing near a large power transformer gave less milk.

A few researchers are further developing the JMC theory [15, 16].

2.4 One-dimensional sound propagation, algorithms

Primary and cancellation sound must have the same direction of propagation. It is therefore easier to cancel plane, guided waves in ducts (below the onset frequency of the first lateral mode) than, for example, three-dimensional sound fields in rooms with omnidirectional propagation. In a set-up as sketched in Fig. 2 (which has in principle already been proposed by P. Lueg [5] in 1934) the sound incident from the left is picked up by the microphone and, after some processing, fed to the loudspeaker such that to the right side the primary and the additional signal cancel each other.

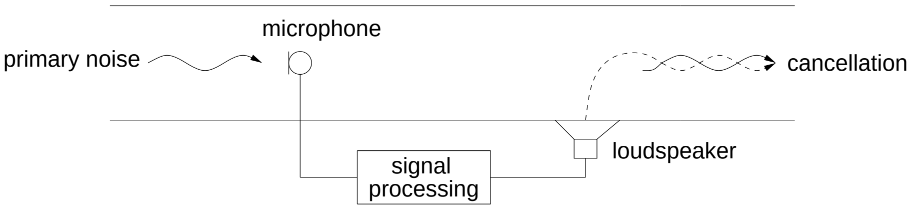

Figure 2. Principle of active feedforward cancellation of sound in a duct.

After Lueg's idea, the "signal processing" should comprise the amplitude adjustment, sign reversal, and time delay according to the acoustic path length. However, an active noise control system is not practically applicable in this simple form. First, the acoustic feedback from the loudspeaker to the microphone has to be avoided and, second, in most cases it is necessary to follow up the transfer function adaptively since the time delay and the sound spectrum can change as a result of temperature drift, superimposed flow, and other environmental conditions. It is therefore common practise today to apply adaptive digital filters which are implemented on fast signal processors to enable online updating. Fig. 3 shows a typical block diagram (amplifiers, A/D and D/A converters, as well as antialiasing lowpass filters being omitted.)

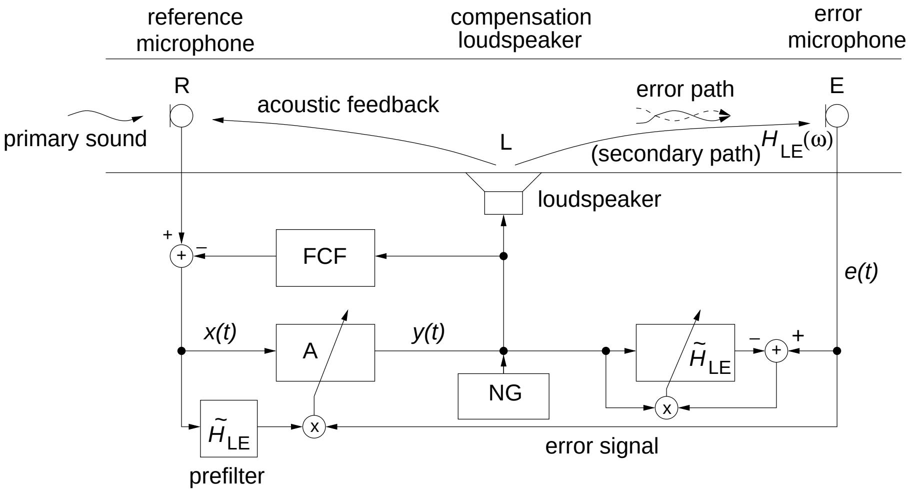

Figure 3. ANC in a duct by adaptive feedforward control with feedback cancellation and error path identification for the filtered-x LMS algorithm.

The transfer function of the acoustic feedback path from the loudspeaker L to the *reference microphone* R is modeled by the feedback compensation filter FCF so that the input signal $x(t)$ to the main filter A does not contain contributions from L. The *error microphone* E receives, in the case of incomplete cancellation, an error signal $e(t)$ which serves for the adaptation of the filter A. This filter adapts such that it models the acoustic transfer function from R to L, including the (complex) frequency responses of R and L. The filters A and FCF are often realised as transversal filters (finite impulse response, or FIR filters), and the most common adaptation algorithm is the *filtered-x LMS algorithm* after Widrow and Hoff [17] where LMS stands for *least mean squares*. The algorithm is controlled by the product $e(t)x(t)$ and adjusts the filter coefficients by a stochastic gradient method so that $x(t)$ and $e(t)$ are decorrelated as far as possible. If the primary sound is broadband, the propagation delay from L to E decorrelates $x(t)$ and $e(t)$ to a certain degree which impairs the performance of the ANC system. In order to compensate for this effect, $x(t)$ is prefiltered in the update path (lower left) with a model $\tilde{H}_{LE}$ of the *error path* H_{LE}. The necessary error path identification is performed with an auxiliary broadband signal of the noise generator NG in the adaptation unit shown at the lower right of Fig. 3. The coefficients of $\tilde{H}_{LE}$ (and also of FCF) are either determined once at start-up and then kept constant or, if the transfer functions vary too much with time, permanently; in the latter case, however, the (weak) auxiliary signal remains audible at the duct end since it is not cancelled by the loudspeaker signal $y(t)$.

After adaptation, the loudspeaker acts as a sound-soft reflector for the wave incident from the left which is, hence, not absorbed but reflected to the left. With a different control strategy the loudspeaker could be operated as an “active absorber”, but the maximum possible absorption is half of the incident sound power; either one quarter are reflected and transmitted. The reason is that it is not possible to achieve perfect impedance matching with a single loudspeaker mounted at the duct wall. The incident wave ‘sees’ the parallel connection of the loudspeaker input impedance and the characteristic impedance of the ongoing part of the duct. (But a loudspeaker at the end of a duct can be driven to perfectly absorb the incident sound [18]).

If the standing waves or the stronger sound propagation to the left in arrangements as those in Figs. 2 and 3 cannot be tolerated, a true active absorber can be realised with loudspeaker pairs or linear arrays [19, 20].

A series of commercial ANC systems working on the principle of sound-soft reflection have been developed by the US company Digisonix and successfully installed mainly in industrial exhaust stacks since 1987 [21]. The filters A and FCF are combined to one recursive, infinite-impulse response (IIR) filter, often applying the Feintuch algorithm [22]. The signal processors allow on-line operation at least up to 500 Hz, suppress tonal noise by up to 40 dB and broadband noise typically by 15 dB. Similar systems have been installed also in Germany [23, 24, 25] and elsewhere [26]. The lower frequency limit is given by pressure fluctuations of the turbulent flow, the upper limit by the computational speed of the signal processor and the lateral dimensions of the duct. The higher modes occurring at higher frequencies can also be cancelled, requiring, however, a greater amount of hardware [27]; therefore, only few such systems with multi-mode cancellation have been installed so far.

The filtered-x LMS algorithm is very popular because of its moderate signal processing power requirement (the numerical complexity is $O(2N)$ if N is the filter length), but its convergence is very slow for spectrally coloured random noise. Fan noise spectra have typically a steep roll-off with increasing frequency so that the convergence behaviour of the algorithm is often insufficient. Efforts have therefore been made to develop algorithms the convergence behaviour of which is independent of the signal statistics, but which can still be updated in real time. One example is the SFAEST algorithm [28] which has a complexity of $O(8N)$. Since it furthermore calculates the optimal filter coefficients in one single cycle, it is particularly useful for nonstationary signals and nonstationary transfer functions. Stability problems in the initialisation period could be solved by the FASPIS configuration which stands for *fast adaptive secondary path integration scheme* [29, 30]. More on algorithms can be found in the books [31] and [32]. The very difficult extension of the fast algorithms and the FASPIS configuration to IIR filters has been accomplished in the doctoral thesis of R. Schirmacher [33].

The modern control theory provides advanced algorithms such as H_∞, H_2, fuzzy control, optimal control, artificial neural networks, genetic algorithms, to name just a few. Overviews are presented, e. g., by the books [34] and [35].

An important concept in many fields of ANC is *adaptive noise cancelling* which became widely known since 1975 by B. Widrow et al.'s seminal paper [36], see Fig. 4: A 'primary' sensor picks up a desired signal which is corrupted by additive noise, its output being s_p. One or more 'reference' sensors are placed such that their output s_r is correlated (in some unknown way) with the primary noise, but does not essentially contain the desired signal. Then, s_r is adaptively filtered and subtracted from s_p to obtain a signal estimate with improved signal-to-noise ratio (SNR) since the adaptive filter decorrelates the output and s_r. This concept, realised by a linear predictive filter employing the least mean squares (LMS) algorithm, has been patented [37] and found wide applications: in speech transmission from a noisy environment [38], in seismic exploration [39], medical ECG diagnostics [40], noise cancelling stethoscopes [41], speech enhancement in noisy environment [42], hearing aids [43], and many other problems. In experimental cosmology, adaptive noise cancelling will be used in the "Low-Frequency Array" (LOFAR) project for the detection of the 21-cm hydrogen radiation from the early universe, which – by cosmic expansion – has been shifted to about 2-m wavelength. The interference by the overwhelmingly stronger signals from terrestric radio transmitters shall be eliminated adaptively [44].

In adaptive feedforward control systems as shown in Fig. 3 the sound propagation path from microphone R to loudspeaker L must be long enough to provide the time required for calculating the signal to be fed to L (*causality condition*). The limiting factor is usually not the computation time in the signal processor but the group delay in the antialiasing lowpass filters which are necessary in digital signal processing.

Problems in technical ANC applications are often posed by the loudspeakers. Very high low-frequency noise levels are typically encountered in exhaust stacks or pipes, demanding for high membrane excursions without nonlinear distortion and, often, robustness against aggressive gases and high temperatures. On the other hand, a smooth frequency response function (as for Hi-Fi boxes) is not an issue because frequency irregularities can be accounted for by the adaptive filter. Special loudspeakers for ANC systems have been developed [45]–[48].

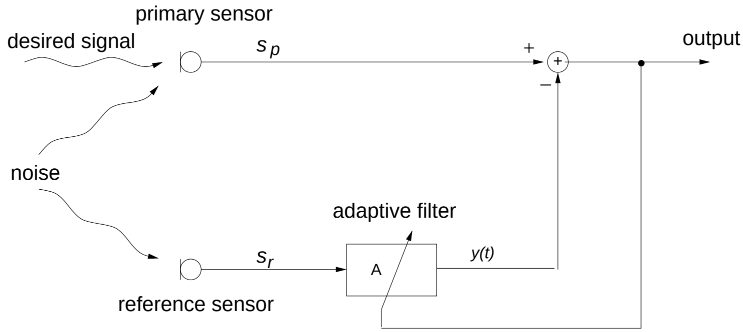

Figure 4. Adaptive noise cancelling.

2.5 Interaction of primary and secondary sources

The ANC systems discussed in the preceding sections are aimed at absorption or at least reflection of the primary sound power, tacitly assuming that the primary power radiation is not influenced by the cancellation sources. However, if it is possible to reduce the primary sound production by the operation of the secondary sources, this will be a particularly effective method of noise reduction.

A monopole radiator of radius a with a surface particle velocity v produces a volume velocity $q_0 = 4\pi a^2 v$. The sound power radiated into a medium of density ρ and sound velocity c at a frequency ω (wavelength λ, wave number $k = 2\pi/\lambda$) is $P_0 = \rho\omega^2 q_0^2/(4\pi c)$. Adding an equal but antiphase monopole at a distance $d \ll \lambda$, produces a dipole which radiates the power $P_1 = P_0(kd)^2/3$. Supplementing this dipole with another one to form a quadripole, the radiated power is further reduced to $P_2 = P_0(kd)^4/15$, assuming $kd \ll 1$ [49, Chapter 7.1].

These conditions are correct if the volume velocity q is the same in all three cases, but this is not necessarily so because ANC, by adding a compensation source in close proximity, does not only raise the multipole order, but can also alter the radiation impedance $Z_r = R_r + j\omega M_r$. The surrounding medium acts upon a monopole with the radiation resistance $R_{r0} = 4\pi a^2 \rho c$ and the mass load $M_{r0} = 4\pi a^3 \rho$ (three times the replaced fluid mass), upon a dipole with $R_{r1} = R_{r0} \cdot (ka)^2/6$ and $M_{r1} = M_{r0}/6$, and on a quadripole with $R_{r2} = R_{r0} \cdot (ka)^4/45$ and $M_{r2} = M_{r0}/45$ [49]. The mass load leads to a reactive power, an oscillation of kinetic energy between primary and secondary source ("acoustical short-circuit"). The product $v^2 R_s$ determines the radiated (active) power. The particle velocity v of the primary source depends on its source impedance and the radiation resistance. A "low-impedance" source (sound pressure nearly load independent) reacts on a reduced radiation resistance R_s with enhanced particle velocity v so that the reduction of radiated power by the higher multipole order is partially counteracted. But the sound radiation of impedance-matched and of "high-impedance" (velocity) sources is reduced in the expected way by an antiphase source in the nearfield.

These relationships can be utilised, e. g., for the active reduction of noise from exhaust pipes (ships, industrial plants, automobiles with internal combustion engines). A large demonstration project was implemented as early as 1980: the low-frequency hum (20 to 50 Hz) from a gas turbine chimney stack was cancelled actively by a ring of antisound sources [50]. Each loudspeaker was fed from one microphone pair through amplifiers with fixed gain and phase settings. Such a simple open-loop control was sufficient in this case due to the highly stationary noise and its narrow frequency band.

The pulsating gas flow emanating from a narrow exhaust pipe is a very efficient "high-impedance" monopole sound radiator; an adjacent antiphase source turns it into a dipole or, in the case of a concentric annular gap around the exhaust mouth, into a rotationally symmetric quadripole. Such "active mufflers" for cars have often been proposed (e. g., [51]), but practical installations are still lacking, for technical and economical reasons: microphones and loudspeakers beneath the car body must be protected against shock and vibration, splash water, thrown-up gravel and the hot, aggressive exhaust gas [52]. Furthermore, active mufflers have to compete with the highly efficient and comparatively cheap conventional mufflers from sheet metal. Researchers in the muffler industry are, however, still developing and improving active systems, testing prototypes, and they are optimistic that active mufflers might go into production because they combine noise cancellation with backpressure reduction; perspectives to include sound quality design are seen, too [53].

2.6 Waveform synthesis for (quasi)periodic noise

A conceptually simple adaptive algorithm has been developed by a British research team [51]. It assumes (quasi)periodic noise, the source of which is accessible for obtaining synchronisation pulses (e. g., vehicle engine noise). The principle is explained in Fig. 5. A loudspeaker is mounted next to the exhaust pipe end, and is fed from a

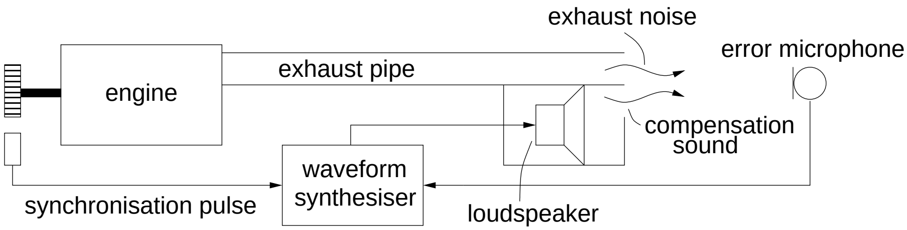

Figure 5. Active cancellation of (quasi)periodic noise by tracking control with sync input and waveform synthesis (after [51]).

waveform synthesiser, realised with digital electronics. An error microphone is placed in the superposition zone and yields a control signal by which the loudspeaker output is optimised. The sync pulses (obtained, e. g., by a toothed wheel and an inductive probe) guarantee that the compensation signal tracks the changing engine rotation speed automatically. The waveform is adapted using a trial-and-error strategy either in the time domain or, faster, in the frequency domain. In the latter case, the amplitudes and phases of the (low order) harmonics of the engine noise are adapted. The prominent feature of this active system is that no microphone is required to receive the primary noise because the signal processor performs the waveform synthesis by itself. The loudspeaker must only provide the necessary acoustic power; resonances, nonlinearities and ageing are automatically accounted for. A disadvantage is the slower convergence as compared to "true" adaptive algorithms.

An example for a technical application of ANC with waveform synthesis in medicine is a noise canceller for patients undergoing a magnetic resonance imaging (MRI) inspection. The electrical high-current impulses needed to build up the required high magnetic fields cause, by magnetostriction and "wire forces", an annoying impulsive noise which is cancelled with the help of an active headset (see Section 2.7). Because no ferromagnetics and preferably no metal at all must be brought into the MRI tube, pneumatic headsets with long plastic tubes as sound guides have been developed for this purpose which are fed from a signal processor with a simple feedforward control and fixed filters [54]. Since, however, the compensation is not very good, an improvement with a metal-free optical microphone for controlling an adaptive filter has been developed [55, 56, 57]. A different approach is aimed at controlling the structural vibrations of the MRI tube walls [58, 59].

2.7 Small volumes — Personal noise protection

An acoustically simple ANC problem is presented by an enclosure the dimensions of which are small compared with the wavelength even at the highest frequencies of interest. The sound pressure is then spatially almost constant, and the cancelling source can be placed anywhere in the enclosure. Correctly fed, it acts as an active absorber.

One such small enclosure is the space between a headphone and the ear drum. The concept of "personal noise protection" by actively controlled headphones was originally claimed in a Russian patent application [60], but reliable signal processing was, in spite of intense research work in many countries, possible only very much later. Independent developments by the US company Bose [61] and Sennheiser in Germany [62] resulted in active headsets for aircraft pilots; active headsets are meanwhile also produced by other companies, being offered as pure hearing protectors in open or closed construction, with feedforward and feedback control in analog electronics, and also with a signal input for telecommunication. The initially very costly active headsets have become so much cheaper that a wider application in vehicles and noisy working places appears realistic. Quite recently, also adaptive digital signal processing is being applied to active headsets and hearing protectors [63].

2.8 Local cancellation

Placing an anti-source in the immediate nearfield of a primary noise source gives a "global" effect as explained in Section 2.5, but if the distance of the two sources gets wider, then only a local cancellation by interference remains [11]. Such systems did not receive general attention as noise cancelers because of their very limited spatial range of efficiency (in the order of $\lambda/10$). But local cancellation can be very useful for acoustic laboratory experiments, such as head-related stereophony when dummy head recordings are reproduced by two loudspeakers [64]. As the sound radiated from the left loudspeaker should be received by the left ear only, a compensation signal is superimposed onto the right channel which compensates the sound coming from the left loudspeaker to the right ear, and vice versa, see Fig. 6. As compared to the familiar source localisation between the loudspeakers of a conventional stereo set, this procedure provides true three-dimensional sound field reproduction with source localisation in any direction, including elevation, and also gives a reliable depth impression.

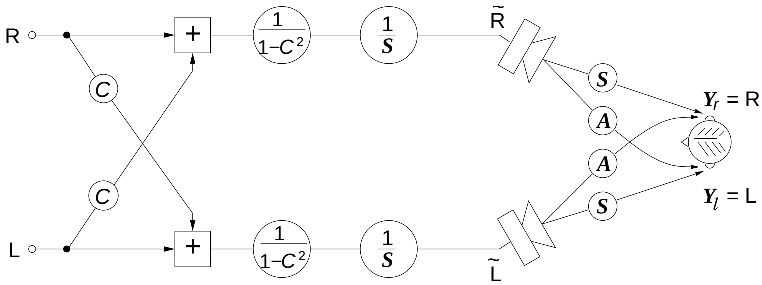

Figure 6. Crosstalk cancellation in head-related stereophonic sound field reproduction with two loudspeakers by prefiltering. $S = S(\omega)$ and $A = A(\omega)$ are the nearside and farside transfer functions, respectively, between loudspeakers and eardrums; circles to the left from the loudspeakers indicate filters with inscribed transfer functions, $C = C(\omega) = -A(\omega)/S(\omega)$.

Of great practical relevance is local active sound field cancellation for teleconferencing and hands-free telephones (speakerphones) in order to eliminate, at the microphone location, acoustic room echoes which degrade the speech quality and tend to cause howling by self-excitation; the active system causes dereverberation of the room response [65, 66]. Echo cancellation and a speech enhancement system for in-car communication has been described in [67]. Echo cancellation for stereophonic sound field reproduction is more involved than single channel applications. Solutions are presented, e. g., in [68] and [69]. The psychoacoustic aspect of masking has been introduced in acoustic echo cancellation combined with perceptual noise reduction [70]. For echo cancellation in fast changing environments, a special algorithm has been developed [71].

A hot topic in speech transmission with multiple not precisely known sound sources is *blind source separation*, using microphone arrays and algorithms such as spatial gradient estimation, independent component analysis (ICA), statistical source discrimination, maximum likelihood, and Kalman filters; [72] presents a comprehensive survey.

A related older problem is the removal of electric line echoes in long-distance telephony with satellite communication links where the long transmission path leads to audible echoes which greatly disturb speech communication [73]. The signals are reflected from an impedance mismatch at the so-called hybrid where the two-wire line branches into the four-wire local subscriber cable. The geostationary satellites are positioned at 36 000 km height so that the echo return path (transmitter → satellite → receiver → satellite → transmitter) is 4×36 000 km which yields, in spite of the signal propagation at the speed of light, an echo delay time of as much as nearly 0.5 s. All satellite telephone links are therefore equipped with transmission line echo compensators (see, e. g., [74]).

Locally effective ANC systems with compact microphone/loudspeaker systems in feedback configuration have been described by H. F. Olson [7] as early as 1956; they absorb low-frequency sound in a narrow space around the microphone and have been proposed for aircraft passengers and machine workers [75]. Because of the very restricted spatial field of efficiency, such systems did not receive general attention. In more recent experiments the test persons disliked also the strong sound level fluctuations when they moved their head.

The application of acoustic echo cancellation has also been proposed for ultrasonic testing where flaw echoes can be masked by strong surface echoes. It is possible to subtract the latter from the received signal and so improve the detectability of flaws [76, 77]. Similarly, the ANC technique can be applied to cancel the reflection of the ultrasonic echo from the receiver [78].

2.9 Three-dimensional sound fields in enclosures

The active cancellation of complex sound fields in large rooms, possibly with non-stationary sources and time-varying boundary conditions, is far beyond the scope of present ANC technology. More realistic is the concept of reducing room reverberation by placing active absorbers along the walls. The incident sound is picked up by microphones which feed the loudspeakers so that their acoustic input impedance is matched to the sound field. The situation is the same as in Fig. 1 if the enclosure walls are considered as a Huygens surface. The loudspeakers can also be driven such that their reflectivity takes arbitrary values in a wide frequency range (experimentally, reflection coefficients between 0.1 and 3 have been realised). This would facilitate the construction of a room with adjustable reverberation time [79], but at present still with a prohibitive amount of hardware.

The concept of active impedance control was originally propagated by our Göttingen team [80, 81] and has stimulated many later research activities, (e. g., [82]–[86]).

Intensive research has been devoted to the active cancellation of sound in small enclosures such as vehicle, aircraft and helicopter cabins. Four-stroke internal combustion engines have an inherent unbalance at twice the rotational speed (the "second engine order") which often coincides with the frequency of the fundamental cabin resonance of cars, so exciting the highly annoying "boom". Since this noise is strongly synchronised with the engine speed its active cancellation is possible with a relatively small amount of hardware and software [87]. It has, however, only been offered in a production car for some time by Nissan for their model *Bluebird* in Japan. Many other car manufacturers develop their own systems, and some of them have successfully built prototypes, but all of them are hesitating for several reasons to install the ANC systems in series production (e. g., within a "comfort package" at extra cost). One argument is that customers would complain if they pay for noise reduction, and there still remains some disturbing noise.

More involved than the “boom” control is the cancellation of the broadband rolling noise, both inside and outside the car. Laboratory experiments and driving tests have led to preliminary solutions; the nonstationarity of the noise input and of the acoustic transfer functions demand for fast adapting algorithms, also for the error path identification [88, 89, 29, 33]. The noise and vibration problems are becoming more severe with small low-consumption cars now under development; they will possibly be equipped with both active noise control for the interior space and active vibration control for the engine and wheel suspensions. For more luxurios cars the trend in the automobile industry goes to combining ANC technology with “sound quality design” for the car interior so that the driver has the choice, e. g., of a more silent car or a more sportive sound [90]–[93].

For economical reasons, the aircraft industry has replaced jet engines by propeller (or turboprop) aircraft for short and medium distances which are, however, much louder in the cabin. Relatively little effort is necessary to employ a technology known as *synchrophasing*. The eddy strings separating from the propeller blade tips hit the fuselage and excite flexural vibrations of the hull which radiate sound into the cabin. If the right and left propeller are synchronised so that their “hits” meet the fuselage out of phase instead of simultaneously, then higher-order shell vibrations are excited which radiate less and so reduce the noise level inside [94]. Better results, however with more involved installations, are obtained with multichannel adaptive systems. An international European research project with the acronym ASANCA has resulted in a technical application [95].

An important issue in ANC applications to three-dimensional sound fields is the placement of microphones and loudspeakers. Attention has to be paid not only to causality, but also to *observability* and *controllability*, in particular in rooms with distinct resonances and standing waves (*modal control*). If, for some frequency, the error microphone of an adaptive system is positioned in a sound pressure node, it does not receive the respective frequency component or room mode so that no cancelling signal will be generated and no adaptation is possible. If the loudspeaker is placed in a node, then a compensation signal calculated by the processor cannot effectively be radiated into the room, which usually forces the adaptive processor to produce higher and higher signal amplitudes, finally leading to an overload error of the digital electronics.

2.10 Freefield active noise control

Technical applications of ANC to three-dimensional exterior noise problems are still quite rare, but many research projects have been reported and a number of patents exist. The problems with active mufflers for cars with internal combustion engines have been discussed in Section 2.5. A technically similar problem is the fly-over noise of propeller aircraft which mainly consists of two components: the propeller blade tip vortex threads, and the equally impulsive exhaust noise. If the exhaust tail pipe is shifted to a position near to the propeller plane, and if the angular position of the propeller on its shaft is adjusted so that in downward direction the pressure nodes of one source coincide with the antinodes of the other one, then the destructive interference reduces the fly-over noise by several dB [96].

A method for reducing traffic noise by cancelling the tyre vibrations of an automobile is disclosed in a patent [97], proposing electromagnetic actuation of the steel reinforcement embedded into the tires.

A frequently investigated problem is the cancellation of power transformer noise, the annoying hum of which consists of multiples of the power line frequency (50 Hz, in USA 60 Hz). It is a seemingly simple problem because of the strong periodicity and the readily accessible reference signal. Several methods have been proposed, either by loudspeakers arranged around the site [98], by force input to the oil in which the transformer is immersed [99] or to the surrounding tank walls [100], or by sound insulating active panels enclosing the transformer [101]. Experimental results are discussed in [102]. Problems are posed, however, first, by the weather-dependent sound propagation – wind and temperature gradients tilt the wave front [103]—and second, because the hum spectrum depends on the electrical load of the transformer [104].

It has also been tried to actively improve sound shielding noise barriers along roads, in particular to cancel the low frequency noise diffracted around the barrier top. The idea is to place loudspeakers along the upper edge and to drive them with adaptive feedforward control, the reference microphones being placed on the roadside and the error microphones in the shadow zone [105]. Improvements are concerned with multiple loudspeaker arrays also along the side walls of the noise barrier [106], or multiple reference control and virtual error microphones [107].

3 Active vibration control (AVC)

3.1 Early applications

In contrast to active noise control, active vibration control has long been applied, in particular to ships. [108] (1905) reports on vibration reduction on a steam ship by synchronisation of the two engines in opposite phase, [109] (1934) on the reduction of roll motion by an actively driven Frahm tank (water is pumped between tanks located on the two sides of the ship), and [110] (1945) on roll stabilisation by bouyancy control with “activated fins”, auxiliary rudders with variable angle of attack protruding laterally from the ship hull into the water. The latter technology is still practised today.

Active damping of aircraft skin vibrations has been proposed by [111], providing multichannel feedback control with displacement sensors and electromagnetic actuators, mainly in order to prevent fatigue damage.

Early publications can also be found on the active control of vibrations in beams, plates and composite structures. In mechanical wave filters where a desired longitudinal wave mode in a bar is superimposed by an interfering detrimental flexural wave mode, the latter can be damped by pairs of piezoelectric patches on either side of the bar which are connected through an electrical resistor [112].

In special environments, e. g., ultrahigh vacuum, magnetic bearings without lubricants are preferred for rotating machinery, but their inherent instability requires feedback control which equally reduces vibrations [113].

An early NASA patent [114] provides an active mass damper (see Section 3.4) to cancel structural vibration.

In the 1980s, longitudinal vibrations of the ship superstructure caused by nonuniform propulsion have been reduced with a type of dynamic absorber, realised by a *centrifugal pendulum*. This is a pendulum swinging along the length direction of the ship and rotating about an axis pointing also in lengthwise direction. The swinging of the pendulum is synchronised to the ship's vibration by controlling the rotational frequency, and hence the centrifugal force, which together with gravity determines its natural frequency [115].

3.2 AVC for beams, plates and structures

Aircraft and spacecraft have a great impact on investigations in active control of structural vibration. Other than the above-mentioned whole-body vibrations of ships which are comparatively easy to control due to their very low frequencies, one is here confronted with elastic structures, i. e., continuous media with an infinite number of degrees of freedom the control of which presents fundamentally different problems. First, there are the different wave types in solids (of which longitudinal, torsional and transversal waves are the most important), their control demands various types of actuators and sensors. Furthermore, the propagation speed is generally higher in solids than in air so that causality problems occur with broadband adaptive feedforward controllers. As a consequence, many problems are treated with modal control where, especially in case of overlapping modes, the *control spillover* problem has to be considered: the unwanted excitation of additional modes the resonance curves of which extend to the controlled frequency. In Fig. 7 it is assumed that the Nth mode, resonant at frequency f_N, shall be controlled; the tails of the neighbouring resonance curves have nonnegligible amplitudes at f_N (the dots on the dashed line) and are therefore also excited by the control signal at f_N, to some extent. Owing to the phase slope around a resonance, the neighbouring modes are usually enhanced rather than damped when the Nth mode is suppressed. While control spillover leaves the system stable, *observation spillover* can produce instability [116].

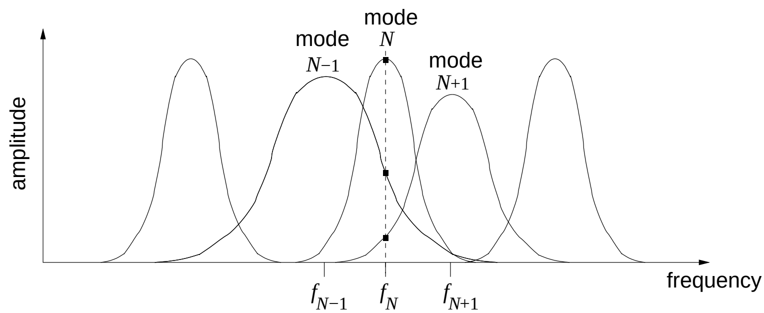

Figure 7. Spillover: attempting to control mode N at its resonance frequency f_N also excites neighbouring modes $N-1$ and $N+1$ with lower, but finite amplitudes.

For satellites, the damping of modal vibrations is important after pointing position manoeuvres etc. since they are built from low-loss materials, and air friction is not present in space. The optimisation of number and placement of sensors and actuators for the mostly applied adaptive feedback controllers requires precise knowledge of the structural dynamics so that reliable modelling in state-space coordinates and a realistic estimation of discretisation errors are possible. An introduction to this field is given by Meirovitch [116].

Damping and stiffness control in mechanical junctions can also be achieved by dry friction control where the pressing force is controlled by a piezoelectric actuator, in feedforward or feedback control, typically by a nonlinear algorithm, e. g., a neural network [117], or by on–off control [118].

In aircraft technology, active controllers have been developed for manoeuvre [119] and gust load alleviation [120], as well as for wing flutter control [121], and for noise and vibration reduction in helicopters [122], in particular by *individual blade control* (IBC) [123] and *higher harmonic control* (HHC) [124]. A major German research initiative was the “Adaptive Wing Project” [125], aimed at aircraft drag reduction by boundary layer and flow separation control with the help of wing shape control, realised by an adjustable lengthwise tiny bump near the trailing edge of the wing, with piezoelectric or shape memory alloy actuators.

Initially, technical problems were encountered, among others, by the fact that sensor and actuator materials such as piezoceramics, piezopolymers, electro- and magnetostrictive materials, shape memory alloys, electro- and magnetorheological fluids are no constructional materials with a mechanical strength sufficient for load-bearing structures; some of them are also too brittle or too weak for fail-safe operation. This led to a new research field since the end of the 1980s: the development of modern compound materials with embedded sensors and actuators (keywords are *intelligent* or *smart materials*, *bi-functional elements, adaptive* or *smart structures, adaptronics, structronics*) [126, 127, 128]. Much information on these research fields is published in the special journals “Journal of Intelligent Material Systems and Structures” (since 1990), “Smart Structures and Materials” (since 1992), in the Proceedings of the “International Conferences on Adaptive Structures and Technologies (ICAST)”, and of the “Adaptronic Congresses” held in Germany since 1996.

Active vibration control has found a popular application in digital cameras with *image stabilisation*. The image blur by camera shake during the exposure is avoided by actively shifting the position of the CCD chip with a piezo-actuator, in response to a motion sensor signal [129].

3.3 Active vibration isolation

Possibilities for active noise control in road vehicles have been discussed in Section 2.9. The predominant sources of interior noise are engine and wheel vibrations which propagate as structure-borne sound through the car body and finally radiate as airborne sound into the cabin. It is therefore reasonable to develop active engine mounts and active shock absorbers which are stiff enough to carry the static load, but dynamically resilient so that vibrations are not transmitted. Piezoceramic actuators are suited for excursions in the submillimetre range [130]; for larger amplitudes and forces at frequencies of a few Hertz, hydraulic and pneumatic actuators are available [131]. Compact and robust combinations of conventional rubber mounts with electrodynamically driven hydraulics have been constructed as *active hydromounts* for a wide frequency range [132]. Active mounts are, for example, standard components of the DaimlerChrysler Mercedes CL Coupé [133].

In helicopter cabins, the principal noise source is the gear box, the vibrations of which are transmitted through typically 7 struts to the cabin roof (as structure-borne sound), and then radiated into the cabin as airborne sound. Particularly annoying are tonal components between 700 Hz and 4 kHz. The vibration transmission has been reduced by piezoelectric actuators at the struts so that the noise level in the cabin became much lower, as was verified in ground tests. The development towards a technical product is a current research topic [134].

Active control technology has been applied for improved vibration isolation of tables for optical experiments, scanning microscopes, vibration sensitive semiconductor manufacturing stages, etc. Commercial products are offered by several companies, e. g., Newport (USA), Technical Manufacturing Corporation (TMC, USA), Halcyonics (Germany), and Integrated Dynamics Engineering (IDE, Germany); the latter company also offers active compensation systems for magnetic strayfields which is important for high resolution electron microscopes etc. Information is available from the companies' homepages.

For satellite missions, sophisticated controllers have been designed to actively isolate facilities for microgravity experiments from structural vibrations which are caused by position controllers and other on-board machinery [130, 135].

The performance of hydraulic shock absorbers can be improved by applying electrorheological fluids (ERF) [136]. ERF are fine suspensions of polarisable small dielectric particles in an unpolar basic fluid, e. g., polyurethane in low-viscosity silicone oil [137]. Their viscosity can be adjusted reversibly between watery and pasty by applying electrical fields of several kV/mm.

Also suitable are magnetorheological fluids (MRF), suspensions of small ferromagnetic particles in a basic fluid, requiring a magnetic field for the viscosity to be changed. The field is usually applied by electromagnets which require high electric current instead of high voltage [138]. In order to provide a wide range of viscosity control, the viscosities of the basic fluids selected for ERF and MRF are as low as possible, which leads to sedimentation problems, in particular with MRF because of its specifically heavier particles than in ERF.

Nevertheless, much research is focusing on MRF applications: earthquake protection of buildings [139], journal bearings of rotating machinery [140], truss structures in spacecraft [141], vehicle suspensions [142], sandwich beams [143], cable swaying [144], adjustable dynamic absorbers for flexible structures [145], squeeze film dampers [146], and many other systems.

3.4 Civil engineering structures

Wind-induced swaying of tall, high-rise buildings can amount to amplitudes of several metres in the upper floors. This low-frequency sway can be reduced by tuned mass dampers (TMD) acting as resonance absorbers: masses of about 1 % of the total mass of the building are placed on the top floor and coupled to the building structure through springs and dampers. Their performance is raised by actively enhancing the relative motion. A prominent example where such an *active TMD* has been installed is the Citycorp Center in New York [147]. Less additional mass is required for aerodynamic appendages, protruding flaps that can be swivelled and utilise wind forces like sails to exert cancelling forces on the building [148].

Many research activities in the USA, Canada and in particular Japan are aimed at the development of active earthquake protection for buildings where, however, severe technical problems have still to be solved [149, 150].

For slim structures such as antenna masts, bridges etc., tendon control systems have been constructed for the suppression of vibrations by controlled tensile forces acting in different diagonal directions [151, 152].

3.5 Active and adaptive optics

The quality of pictures taken with optical or radio astronomical mirror telescopes depends essentially on the precision to which the optimal mirror shape is maintained. Modern swivelling large telescopes suffer from deformation under their own weight which is compensated more efficiently by active shape control than by additional stiffeners which inevitably enhance the mass of the structure. This technology is called *active optics* [153, 154].

While the telescope motions are very slow (time constants above 0.1 s) and therefore easy to control, *adaptive optics* have solved the more complicated problem of controlling picture blurring by atmospheric turbulence, the so-called *seeing* which fluctuates at frequencies about 1000 Hz. The large primary mirror is fixed, but the smaller secondary mirror surface rests on a matrix of piezoceramic actuators which are adjusted by an adaptive multichannel controller so that a reference star is optimally focused. If no reference star exists in the vicinity of the observed object an *artificial guide star* can be created by resonance scattering of an intense laser beam from sodium atoms at about 100 km height [155, 156]. Adaptive optics have improved the optical resolution of the best telescopes by a factor of 10 to 50, to almost the diffraction limit.

This technology was developed in the USA during the 1970s for the military SDI project and has been declassified not before 1991 when civil research had reached almost the same state [157]. Meanwhile, this technology is applied to nearly all modern large optical infrared telescopes such as the *Gemini North Telescope* on top of the Mauna Kea on Hawaii [158] and the *Very Large Telescope* (VLT) in Chile, and will be applied to even larger telescopes planned for the future [159, 160].

Adaptive optical mirrors have also found applications in industrial production for laser cutting and welding [161], and generally for optimising the quality of high-intensity laser beams [162, 163]. Other non-astronomical fields of adaptive optics application are confocal microscopy [164], *spatial light modulators* (SLM) for optical telecommunication [165], and ophthalmology [166]. Most of the small deformable mirrors are manufactured as micromechanical systems (MEMS) (e. g., [167]). A survey of industrial and medical applications of adaptive optics is presented in [168]. The growing importance of this field can also be seen in the fact that many textbooks on adaptive optics have been published (e. g., [169]–[173]).

3.6 Noise reduction by active structural control

Active control of structural vibrations and active control of sound fields have been developed almost independently, including differing control concepts (mostly feedforward in acoustics, mostly feedback in vibration). But since some time the two fields have become connected. Many noise problems result from radiation of structure-borne sound, e. g., into the interior of cars and aircraft, on ships, by vibrating cladding panels of machines, etc. Here comes into action a concept known under the acronym ASAC (*Active Structural Acoustic Control*) [174] where noise reduction is not attained by superimposing airborne sound to the disturbing noise field but by controlling the vibrating structure itself. This is possible by suitably placed and controlled actuators to suppress the structural vibration, although this is not necessarily the optimal solution.

Acoustically relevant are mainly plate bending waves which due to their frequency dispersion ($c_B \propto \sqrt{\omega}$) are non-radiating at low frequencies and strongly radiating above the *critical frequency* ω_g at which the bending wave velocity equals the sound velocity c_0 in the surrounding medium. If $c_B < c_0$, the acoustical short-circuit between adjacent wave crests and troughs yields a weak sound radiation into the farfield, but for $c_B > c_0$ a very effective radiation results. The proportionality factor in $c_B \propto \sqrt{\omega}$ contains the flexural stiffness so that its modification shifts the critical frequency and can turn radiating modes into non-radiating ones (*modal restructuring*). Much work has been done to investigate how, e. g., by laminates from sheet metal and piezolayers as sensors and actuators, adaptive structures can be constructed which can suppress, in propeller aircraft etc., the above-mentioned fuselage excitation by eddy threads, so enabling a substitution for or at least a supplement to the more involved (and heavier) direct noise control by mirophone/loudspeaker systems [175, 176, 177].

3.7 Sound transmission control

Sound transmission through walls, windows, sound shielding plates etc. is effectively controlled by active means. This is often achieved by ASAC (see preceding chapter), but in some instances also by different means. Experiments have shown that sound transmission through double-glazed windows can be reduced by actively controlled loudspeakers in the gap between the glass panes [178]. Actively controlled double wall partitions are also reported [179] and [180], the latter one for insulating floor impulsive noise.

The favourite actuators for active structural damping are piezoceramics, bonded to the structure to form adaptive (smart) structures [181]. Semi-active approaches apply passive (sometimes actively controlled) shunts across the piezoactuators to save energy [182, 183], or even to gain electrical energy from the vibrated piezos, a rather new technology labelled *energy harvesting* or *energy scavenging* [184, 185].

3.8 Control of nonlinear dynamical systems

The control of nonlinear dynamical systems has gained much attention in recent years, due to the great potential of applications in physics, enginering, medicine, and communication.

Of practical importance is the control of magnetic bearings to stabilise a rotor in its unstable equilibrium by feedback control. Being frictionless and free from lubricants, magnetic bearings are often applied in vacuum apparatus (also in spacecraft) such as high-speed centrifuges (e. g., [186]).

A particular realm of research is *chaos control*, forcing a chaotic oscillation into a stable periodic orbit [187, 188]. Major control concepts are 1) feedforward control [189]; 2) feedback control by applying small perturbations to an accessible system parameter when the trajectory comes close to the unstable periodic orbit where it is desired to stabilise the system, the so-called OGY control (named after the protagonists of this method [190]); 3) *Time Delay Autosynchronisation* or *Delayed Feedback Control*, where the feedback signal is the difference of the actual and a previous output signal of the chaotic system [191]; and 4) *sliding mode control* [192]. An early form of the delayed feedback control concept has been formulated in the theory of balancing rods by humans and bicycle riding [193].

A medical application is the stabilisation of atrial fibrillation, a chaotic rapid oscillation of blood flow in the heart vestibules [194].

A potential application of chaos control is secure communication by masking the message with a broadband chaotic carrier at the transmitter site and demasking it at the receiver site by synchronising the chaotic transmitter and receiver oscillators [195].

An extension of delayed feedback control is *Multiple Delay Feedback Control* where the feedback signal contains more than one previous observables. This concept has been applied successfully, e. g., to the stabilisation of a Colpitts oscillator and a frequency doubled solid state laser [196].

Related to chaos control is *bifurcation control*; an overview outlining the theory, control concepts, and potential applications is given in [197].

While most applications of chaos control are aimed at converting an unpredictable process to a regular one, some other situations favour the transition of regular to chaotic behaviour (*anticontrol* or *chaotification*), such as in combustion engines where chaos (here: turbulence) enhances the mixing of fuel and air and so leads to better performance. Another example where the forced transition of regular oscillation into chaotic motion is beneficial is the improvement of a neural network by state feedback control [198].

For more information about the subject see Chapter **??** in this book.

4 Active flow control

Coherent active control technology is also applied to other fields than sound and structural vibrations, among which the physics of fluid flow is gaining more and more importance. One of the many interactions of sound and flow is the transition from laminar flow of a slim gas flame into turbulence by insonification. Conversely, the turbulence of a flame has been suppressed actively by feedback control with a microphone/loudspeaker system [199].

Laboratory experiments have shown since about 1982 that the transition from laminar to turbulent flow can be shifted to higher Reynolds numbers by controlling the Tollmien-Schlichting waves in the boundary layer, thereby providing drag reduction which is of great technical relevance. This can be achieved with thermal inputs [200], or by acoustical or vibrational excitation [201, 202, 203].

Also, the dangerous surge and stall in compressors, resulting from instabilities, can be suppressed acoustically [204].

An ionised gas stream in a combustion chamber (as in a rocket) tends to produce unstable resonance oscillations which can be suppressed by an appropriately controlled electric d.c. current through the ionised gas, employing a feedback controller with a photoelectric cell as oscillation sensor [205].

A micro-electromechanical system (MEMS) to be mounted on fan blades is presented in [206], comprising a turbulence sensor, an integrated circuit, and an actuator by which turbulence noise can either be reduced, or – in the case of heat exchangers – amplified in order to improve heat transfer. Experiments on this interesting technique have been described in [207], reporting flight control of a delta wing aircraft, and in [208] where the laminar/turbulent transition is influenced along the wing profile in a wind tunnel.

Blade-vortex interaction causing the rattling impulsive noise from helicopters can be reduced by controlling flaps at the trailing edges [209]. Also, helicopter stall can be controlled by trailing-edge flaps [210], or by plasma actuators [211]. In a further development, tip vortices of helicopter blades, aircraft foils, or marine propellers can be reduced by air injection to the high-pressure side of the lifting body [212, 213].

Dynamic stabilisation of jet-edge flow with various adaptive linear feedback control strategies has been experimentally verified by [214]. Disturbing resonances in a large wind tunnel with free-jet test section (the so-called Göttingen model) can be suppressed by feedback ANC, employing multiple loudspeakers [215]. Active flow control can also provide a low-frequency high-intensity sound source, utilising an aeroacoustic instability [216, 217].

Conclusions

Coherent active control systems are commercially applied in acoustics in certain problem areas, but only in acoustically somehow “simple” situations: small volume, one-dimensional sound propagation, quasiperiodic noise, isolated modes. There are many more applications in vibration technology, but there are also fields where the non-application of a well-developed technique is at first sight surprising, among them flutter control of aircraft wings which has been successfully tried since more than 30 years. Here the flutter limit would be shifted to a higher flight speed, but this is not practised from safety considerations: if such an active controller fails, and that cannot be excluded with such complex systems, the danger of wing fracture and hence an air crash would be too high. This is a general problem; precautions have to be taken in safety-relevant applications where failure of the active control system must not have catastrophic consequences.

The general interest in active control of noise and vibration has been steadily increasing, a fact which can also be concluded from the growing number of textbooks, special conferences and journal papers per year. Based on the author's collection of more than 12 000 references on active control of sound and vibration [218, 219], Fig. 8 shows a histogram of the number of publications grouped in five-year periods. An exponential increase is observed from the 1950s through the early 1980s with doubling every 5 years, followed by further growth at reduced pace (approximately doubling in ten years). There are nearly twice as many papers on active vibration control than on active sound field control, and there are about 7 % patent applications. This is relatively high for a research topic and proves the considerable commercial interest.

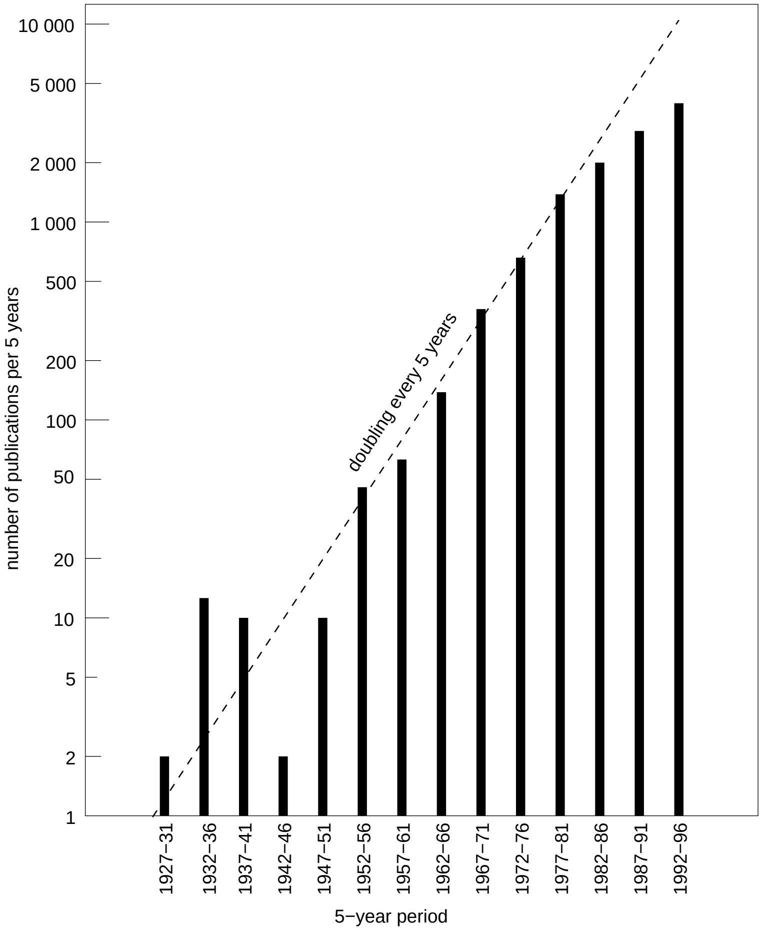

Figure 8. Five-year cumulants of ANVC publications, based on the author's data files.

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