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Patents on Active Control of Sound and Vibration – an Overview –

Second revised and enlarged edition

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PREFACE

Patent titles and patent abstracts often are not really informative. During my work on a patent bibliography it appeared to me therefore reasonable to write this text. Based on about 2060 patent families out of which about 1740 have been selected (removing redundancies and less important ones), this text gives an overview of old and new patents on Active Noise and Vibration Control (ANVC), including related fields such as algorithms, sound design, active flow control, transducers, etc. The patents are grouped in 17 sections which are subdivided into subsections if appropriate. Some emphasis is laid upon patents on algorithms (Section 2).

The References in Section 18 are given in short form; concerning the citation style, see [1].

This text is the second revised and enlarged edition of the first version, published in January 2001 [2, 3].

Although I have done my best to deliver a reliable and useful document, I cannot take any responsibility for the correctness and completeness of the data given.

Göttingen, April 2009 Dieter Guicking

CONTENTS

1. INTRODUCTION

Unlike most other fields in physics, noise and vibration control is a subject where many researchers apply for patents before publishing their results in the open literature. This is even true for fundamental ideas. Early patents on basic principles of active noise control are briefly summarized in the following paragraph.

A fundamental concept in both active noise control (ANC) and active vibration control (AVC) is *feedback*. As a seminal patent on negative feedback systems is considered [4]. The first patents on the idea of active noise control by interference with an anti phase sound wave have been granted to Henri Coanda [5, 6], although his arguments are acoustically incorrect. Widely known are Paul Lueg's German and US patents [7] where the basic idea of active cancellation by superposition with a phase-inverted replica is correctly described for one- and three-dimensional sound fields; the proposed experimental set-ups were, however, far from being applicable to practical situations. First experimental demonstrations were given by H. F. Olson in the 50s, based on two patents [8, 9]: the first one describes a loudspeaker with a microphone just in front, with feedback control to serve as a local sound absorber, the second one is related to active vibration isolation. Various fields of possible applications are listed in both patents. Two further early patents are those granted to M. Brute de Remur on the electroacoustic cancellation of a sound wave passing through an orifice in a baffle [10], and to M. Jessel on the cancellation of sound waves radiated from a given source distribution by an array of Huygens sources (monopoles plus dipoles) distributed along a closed shell surrounding the primary sources [11], the now so-called JMC theory (after Jessel, Mangiante and Canévet). A more recent patent applying this method is [12]. A simple feedback system for (local) free-field cancellation of machine noise is disclosed in [13], employing a conventional loudspeaker or a "stentorphone" where the sound is produced by a modulated air flow. Three patents have been applied for by the German acoustician O. Bschorr in 1969: one describing the basic principle and listing a variety of unconventional sound sources [14] (see also Section 17), the next one applying to noise shielding by a grid of anti sources [15], and the third one to reduction of sound radiation from vibrating panels by distributed or point force input [16], a technology which has later been termed ASAC (an acronym for *Active Structural Acoustic Control*, see Section 9). All these patents have in common that they have never been exploited commercially.

2. ALGORITHMS

Practical applications of active noise control (ANC) and also of many aspects of active vibration control (AVC) became possible only with modern electronics, in particular adaptive digital signal processing. The fact that algorithms are essentially mathematics, and mathematics cannot be patented, can be circumvented by describing the algorithms as block diagrams so that the patents are granted for an assembly of signal processing units. Algorithm patents in this sense will be summarized below in chronological order of first submission.

Before 1970: An early application of active sound cancellation is the "Apparent sound translator" of Atal and Schroeder [17] which applies head-related *crosstalk cancellation* to a stereo set-up with two loudspeakers. Provided that the left loudspeaker is fed by a signal recorded with the left channel of a stereo microphone, the sound from this left loudspeaker should only reach the left ear of the listener. The component yet arriving at the right ear is cancelled by a compensation signal superimposed to the right loudspeaker, and vice versa. The compensation signals are obtained from the loudspeaker input signals by filtering with transfer functions derived from the transfer functions from the loudspeakers to the ears (*head-related transfer functions, HRTF*). More patents based on this method are discussed in Section 4.3. A method of howling prevention in public address systems is disclosed in

[18]: the microphone signal is frequency-shifted by a few Hertz so that positive acoustic feedback is prevented; furthermore, a suppressor is introduced eliminating weak spectral components which are supposed to result from multiply reflected and thereby frequency-shifted reverberant sound. This acoustic feedback stabilization by frequency shift has been re-invented repeatedly [19, 20, 21]. A method of speeding up the convergence of an adaptive line echo canceler is disclosed in [22].

1970–1980: Automatic amplifier gain control is often necessary to obtain a good signal-to-noise ratio, for overload prevention, and to ensure stability. An early patent on this problem is [23], offering a digital feedback controller which provides dynamic level compression of time-varying signals essentially without nonlinear distortion. An important concept in many fields of ANC is *adaptive noise canceling* which became widely known since 1975 by B. Widrow et al.'s seminal Journal paper [24]: A "primary" sensor picks up a desired signal which is corrupted by additive noise, its output being s_p, and 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 essentially not 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). This concept, realized by a linear predictive filter employing the least mean squares (LMS) algorithm, has been patented in [25] and since then has proved to be a valuable tool for many fields.

A nonlinear signal processing strategy of noise reduction from two essentially equal signals with uncoherent noisy distortion (such as in the cocktail-party effect) is outlined in [26]. The task of measuring transfer functions of time-varying systems can be solved by pseudo-random time series as test signals [27].

G. B. B. Chaplin (England) and his coworkers applied for many patents on ANC, starting with a description of non-adaptive and adaptive feedforward systems for active fan noise cancellation in ducts, including feedback cancellation, directional microphones and loudspeaker arrays, and adjustable time-delay units in analog electronics [28]. While in this patent no specific adaptation algorithm is presented, another patent followed on the quasi-adaptive technology of *waveform synthesis*, applicable to essentially repetitive noise and vibration; a trigger signal is required to provide the fundamental period, and the adaptation is performed by a trial-and-error method in the time domain, eventually minimizing an error signal [29]. Two more patents followed on feedforward control with fixed filters, including feedback cancellation [30, 31].

The application of an adaptive filter to another aspect of signal processing, the improvement of the signal-to-noise ratio for narrowband spectra in braodband noise by the LMS algorithm, is the subject of a patent on Widrow's *Adaptive Line Enhancer*, which eliminates uncorrelated signal portions [32].

Adaptive filters tend to go unstable with input signals having a partial frequency band spectrum; they can be stabilized by applying a leaky coefficient update algorithm [33].

Chaplin improved the convergence behavior of his original algorithm [29] by making use of previous error signals [34]. He also applied feedback control for local sound field cancellation [35]. A trial-and-error method, but by digital control in the frequency domain, has been proposed to reduce discrete frequencies from transformer noise and the like [36].

A method for determining the optimum FIR (*finite impulse response*) filter coefficients for a one-dimensional ANC system employing two loudspeakers and two microphones is outlined in [37]. An adaptive correlator for application to, e. g., sonar systems comprises adaptive linear predictors for a plurality of sensor signals and gives estimates of the coherence between one signal and a time-delayed, frequency-shifted version of a second signal [38]. A device for deriving the cancellation signal with appropriate time delay by a shift register is disclosed in [39]. The application of truly adaptive feedforward control for broadband noise reduction in one-dimensional problems employing the LMS algorithm has been proposed in [40]; to avoid feedback instability, the use of directional microphones or electronic feedback cancellation is suggested.

1981–1984: Extensions to [35] are given in [41, 42], and to [40] in [43]. In order to get faster adaptation of the waveform synthesis algorithm, it can be done in the frequency instead of the time domain [44]. When an external synchronization signal is not available, it can be obtained from the error sensor via a filter or a phase-locked loop [45]. A modified adaptive noise canceler with a feedforward frequency domain algorithm and parallel narrowband correlation filters is discussed in [46, 47]. Adaptive filters for echo cancelers often suffer from an inherent nonlinearity in the CODEC; impulse response estimation is improved by inserting a substantially identical nonlinearity in the echo cancellation filter [48].

1985–1990: The fundamentals of adaptive signal processing laid in [24] and [32] have been extended in [49] by applying adaptive line enhancing, adaptive noise canceling and deconvolution for speech improvement and acoustic machine health monitoring by a frequency domain LMS algorithm. While this concept applies primarily to feedforward systems, an extension to feedback systems has been disclosed in [50]. A detailed description of the waveform synthesis method in the frequency domain is given in [51, 52]. Voice communication from emergency vehicles is improved by a digital adaptive comb filter which notches out the siren noise [53].

In 1985 started the patent activities of Nelson Industries/Digisonix Division (USA), beginning with two frequently referenced fundamental patents on adaptive feedforward control with electronic feedback cancellation, without separate feedback path modelling, employing an ARMA (*autoregressive moving average*) filter with the LMS algorithm and some pre-training [54], or without pre-training, but permanent on-line modelling of error and feedback path with the help of a low-level auxiliary noise signal [55]. Another fundamental patent (but not from Nelson Industries) is related to the tracking control of periodic noise in enclosures such as vehicle cabins: A synchronization signal is taken from the engine, a multichannel LMS algorithm is applied to achieve good performance in the whole interior space, and various methods of stabilization are proposed [56].

Stable operation of the LMS algorithm, when applied to input signals with large spectral variations, is obtained by normalization of each frequency bin by use of an input power estimate [57].

A frequency-domain block-adaptive FIR filter has been developed for echo cancellation in speech and data transmission with correlated inputs [58]. A multichannel adaptive frequency domain feedforward algorithm with transfer matrix operations is outlined in [59], for possible applications in unconfined three-dimensional space. In order to increase the dynamic range of the controller without readjustment by the user, a system with automatic gain control has been proposed [60]. A speech detector for a voice-controlled switch operating in a noisy environment is described in [61]; this patent is not directly related to ANC, but speech detection is also important for noise suppression from distorted speech signals.

A method to speed up the convergence of an LMS filter for non-white input signals by orthogonalization is disclosed in [62], [63] and [64].

A device for monitoring the performance of an ANC or AVC system is described in [65] which also permits testing and operator controlling of the system. The frequency range of stable operation can be extended by narrowing the error signal spectrum [66]. Tracking control with a tachometer signal in a multichannel system can be simplified by an orthogonal transform which reduces the cross linked multichannel system to a series of independent single-channel systems [67], [68]. If a desired harmonic signal with accessible source is superimposed by a harmonic disturbance of similar frequency, the resulting beat can be used to eliminate the disturbance by averaging over exactly one period of the disturbance [69].

A comparatively inexpensive digital adaptive tracking control system for the active cancellation of repetitive signals is outlined in [70], the processor receiving synchronization and error signals, and comprising a delay estimator to keep the cancellation signals in a stable phase interval. The standard one-dimensional adaptive feedforward control with an FIR filter, the filtered-x LMS algorithm and feedback cancellation with a separate FIR filter, utilizing a pseudo-random auxiliary signal for error path and feedback path modelling is also described in [71] which is essentially a re-invention of [54].

A detailed description of a multichannel tracking control system for repetitive noise or vibration is given in [72] where, for each frequency component, sine and cosine canceling signals are generated from the synchronization pulses, the weighting coefficients being controlled adaptively with a leaky, variable step size, least squares algorithm. Many systems are typically applied to one-dimensional sound propagation in ventilation ducts. Faster convergence can be achieved by selecting filter coefficients close to the final ones in response to measured input data [73]. An adaptive line enhancer using adaptive noise canceling and variable step size in the update circuit is disclosed in [74]. A multichannel adaptive tracking algorithm for repetitive noise with known fundamental frequency is outlined in [75], utilizing an auxiliary test signal for determining the transfer function matrix between the actuator and sensor arrays. The application of the multichannel filtered-x LMS algorithm to three-dimensional sound fields including crosstalk cancellation is the subject of [76].

Without auxiliary test signal for the transmission path modelling works the principle of *overall modelling* [77]. A combined feedforward and feedback control scheme as opposed to adaptive feedforward control has been proposed for underwater and structure-borne sound [78]. ANC and AVC by multichannel systems with correlated inputs is possible by special signal processing [79]. If complete cancellation of the noise is not wanted, adaptation to a desired sound ("noise shaping") is possible by some modification of the algorithm [80]. A system similar to that of [55], but with noise shaping to get a desired residual signal rather than complete cancellation is described in [81]. The filtered-x LMS algorithm for adaptive feedforward systems can be simplified by replacing the prefilter in the update path with a simple delay which approximates the delay in the combined loudspeaker–error microphone transfer function [82]; this "delayed-x LMS algorithm" requires less hardware and performs nearly as well as the filtered-x algorithm.

An ANC system, applicable to electroacoustic communication etc., cancels repetitive disturbances "in-wire," i. e., electronically by sort of adaptive noise canceling [83]. A digital adaptive feedback ANC system which is robust against phase shift by changing sound propagation conditions is disclosed in [84].

1991: The convergence of an adaptive ANC algorithm is speeded up by the *estimate-maximize algorithm* where after initialization with the complete input data set, an incomplete data set with off-line predictive control is employed [85]. Multichannel adaptive feedforward ANC with crosstalk cancellation is the subject of [86]. Speed-up of the multichannel LMS algorithm by a coordinate transform into modal coordinates separates the multichannel system into a number of uncoupled systems [87]. A feedback control system with the filtered-x LMS for quasi-periodic noise is outlined in [88] including desired signal recovery and a period detection unit to enable rapid tracking of changes in the primary noise frequency.

Typical problems occurring with the filtered-x LMS algorithms (such as poor convergence with colored spectra, lacking observability and controllability in case of low coherence of input and error signal) are promised to be solved by a correlation or coherence or whitening filter in the error path, instability being avoided by inputting only well-behaved signal components to the adaptive filter update section [89, 90].

An adaptive feedforward control system with frequency band splitting and different sampling periods in the parallel channels is proposed for the application of ANC and AVC in prime movers [91]. ANC for tracking feedback control of repetitive sound with individual filters (e. g., switched capacitor filters) for each harmonic is proposed in [92], [93]. A filtered-x LMS algorithm for adaptive cancellation of repetitive noise, echoes, etc. is outlined in [94] where the speed of computation is enhanced by sampling with fewer values per period for the higher-frequency components. Instabilities caused thereby are avoided by coefficient limitation to a prescribed maximum value. The filter coefficient update is performed in a subfilter by a feedback loop, the coefficients being copied to the main filter. A multichannel adaptive feedback ANC or AVC system for correlated noise (periodic, band-limited or otherwise having some predictability) with crosstalk cancellation is described in [95]. The feedback problem of common filtered-x LMS systems is promised to be solved by a pure feedback controller with a predictive estimator. This system is proposed for hearing protectors of air base personnel; good simulation results are obtained for prediction times of about 200 μs [96]. Fault detection of machinery etc. by acoustic signature analysis suffers often from strong background noise; [97] proposes multichannel adaptive noise canceling, applying a pipelined approach to speed up the adaptation.

1992: A filtered-x LMS system for repetitive noise where the prefilter transfer function is selected in dependence upon the fundamental frequency of the noise is described in [98]. A new system identification algorithm (the "MX filter") has been outlined in [99]; it is easy to implement, has low computational complexity, and is well-suited for the on-line modelling of dynamic AVC systems and processes. For ANC of noise with inherent predictability (correlated noise) a feedback control system with an auxiliary test signal is disclosed in [100]. Multichannel adaptive feedforward control with on-line adaptation is the subject of [101].

An unrealistic method of noise suppression is the subject of [102, 103] where the inventors optimistically write that traffic noise etc. can be cancelled by subtracting a signal read from a library where noises recorded from cars, aircraft etc. have been stored.

A frequency domain adaptive ANC or AVC system with sliding FFT instead of block processing is disclosed in [104], with preferred application to internal combustion engine repetitive noise and vibrations, applying tracking control with a synchronization signal taken from the engine.

In [105] special emphasis is laid on the initialization process (system identification with an auxiliary white noise signal) in an adaptive feedforward system for broadband noise cancellation in vehicle compartments. Tracking control of harmonic signals with slowly varying frequency is possible by harmonic filters as outlined in [106]. According to [107], the computational effort of adaptation can be avoided in ANC for periodic noise by employing a time delay unit and inverse filtering. An adaptive feedforward control system with ARMA filter, where the transversal and recursive coefficients are separately updated is proposed in [108].

Tracking control of repetitive signals with widely varying fundamental frequencies by digital signal processing becomes more efficient with a variable sampling frequency [109].

A system with noise shaping to get a desired residual signal rather than complete cancellation, combined with overload prevention of the secondary loudspeaker by power limiting is disclosed in [110]. Indirect error sensing is the subject of [111] where the filtered-x LMS algorithm is applied to local sound field control around the head position of a person (however, it seems to be able to work only for an invariant transfer function from the real to the notional error microphone position).

To circumvent the often problematic time delay caused by the application of adaptive filters in ANC applications, a combination of a low-delay filter with one or more longer-delay filters is discussed in [112]. Improved noise suppression in feedforward and feedback adaptive filters is outlined in [113]. Correlated noise can be cancelled by feedback control (i. e., without input sensor) not only via desired signal restoration from the filter output, but also from the filter input [114]. A multichannel neural network controller to cancel aircraft gas turbine noise is proposed in [115]. An adaptive feedforward control system with on-line error path modelling and fault detection employing an auxiliary noise signal is disclosed in [116].

The filtered-x LMS algorithm in the frequency domain, utilizing in the update branch the cross spectrum of input signal and error signal, is proposed in [117]. An adaptive feedforward control system with on-line error path modelling in the frequency domain, requiring an auxiliary noise signal is described in [118]. A filtered-x LMS system for broadband feedforward control in a duct with prevention of low-frequency overload of the loudspeaker by a high-pass filter is outlined in [119].

1993: An improved method of on-line system identification with a fixed rather than a stochastic test signal is proposed in [120]; this reduces the computational complexity, and avoids coefficient jitter by subtracting from the error signal the component caused by the test signal. The aspect of noise shaping dominates [121] where adaptive feedforward control of sound or vibration is performed such that a desired time or frequency response is obtained, by adapting to a selected or programmed model reference system. Adaptive feedforward control of a multi frequency disturbance by a multichannel system with one adaptive filter for each frequency component outlined in [122].

A method for removing impulsive disturbances from a band-limited desired signal is disclosed in [123], utilizing the fact that impulsive noise has spectral components also in frequency bands adjacent to the signal frequency band, and that a coherent noise canceling signal can be generated from this noise information. A further improvement of the multichannel waveform synthesis algorithm applies a perturbation method to spectral parameters (rather than a trial-and-error procedure), aiming at faster convergence by including correlations or previous data [124].

The realization of a combined feedforward and feedback control algorithm without error path modelling and adaptation in the frequency domain is described in [125], and additionally with non-integer sample delays in [126]. Most LMS applications, however, use an error path model. Its adaptation can also be performed with an auxiliary chirp signal [127].

A digital multichannel ANC or AVC frequency-domain LMS algorithm with block adaptation, variable step size and zero padding is outlined in [128].

ANC or AVC multichannel systems with multiple (partially) correlated sources of repetitive disturbances rely on the cross-spectral density matrices between the reference and residual sensors, providing convergence also for ill-conditioned matrices [129]. An adaptive feedforward ANC system for ventilation ducts with feedback cancellation and explicit system identification (transfer function determination) is described in [130]. ANC with noise shaping, e. g., for automobile mufflers, can be realized by model reference control in the frequency domain [131].

An analog noise cancellation system with digital control of the filter parameters, either in feedback or feedforward mode with virtual earth, is claimed in [132].

The convergence behavior of the filtered-x LMS algorithm for the cancellation of broadband noise can be improved by inserting a whitening filter after the reference sensor, in particular realized by the inverse autocorrelation function of the reference signal [133]. Adaptive feedforward control can also be realized by a multistage lattice filter [134]. The stability of tonal (e. g., engine related) noise cancellation in a vehicle cabin can be enhanced by a phase correction unit accounting for sudden changes of the excitation [135]. Convergence speed and stability of a combined feedforward and feedback adaptive system can be improved by including an error prediction filter and utilizing its output for the filter coefficient update [136]. Speeding up the convergence of the filtered-x LMS can also be obtained by the projection algorithm [137].

Broadband adaptive cancellation, except for spectral bands where compensation is not desired (i. e., feedforward control with a spectral leak), is accomplished by a second error input which selectively drives the measured error to zero [138]. System identification by an adaptive filter, where the output signal is corrupted by uncorrelated noise, is the subject of [139]; an improved coefficient update is provided by adjusting the adaptation step size according to an estimation of the reference (input) signal.

A noise suppression system for speech transmission from a noisy environment is disclosed in [140], applying a frequency domain algorithm with notch filters.

Digital howling prevention for public address systems is disclosed in [141], applying a cascade structure of notch filters and automatic gain control.

1994: An adaptive feedforward control system with a leaky algorithm provides parameter constraints, e. g., output power limitation (to prevent loudspeaker damage) by controlling the leakage coefficient in response to the output signal [142, 143]. To improve speech communication of emergency vehicle crews, a notch (or, comb) filter is proposed to cancel the siren noise [144] (see also [53]). A combination of feedforward and feedback control improves the performance of an ANC system with a leaky filtered-x LMS algorithm [145].

As an alternative to the multichannel filtered-x algorithm, an algorithm is presented in [146] which restores the coherence of input and error signal by filtering the error signal with the time-inversed (and accordingly delayed) plant transfer function, thereby reducing the computational complexity by nearly one order of magnitude. An improved filtered-x algorithm for repetitive noise is disclosed in [147], applying a "complex generator," i. e., a circuit producing in-phase and quadrature components for the sinusoidal noise components and calculating the adaptive filter coefficients therewith.

An alternative cost reducing concept for adaptive feedforward control of periodic noise is presented in [148] where the in-line control filter is realized in analog circuitry, and only the coefficient adaptation is performed digitally. A waveform synthesizer with phase-locked loop and switched capacitor filter is disclosed in [149], providing multiple waves synchronized with the tracking signal, but at different phase shifts. Adaptive feedforward control is improved by coherence optimal filtering so that only such noise components are processed which in principle can be cancelled [150]. A SIMO (*single input, multiple output*) system with a single reference transducer, but multiple output and error channels, including decoupling of the output channels is described in [151].

A multiple error, multichannel recursive algorithm for the cancellation of road noise in a vehicle cabin is presented in [152], with a detailed mathematical description.

Synchronization problems in adaptive feedforward control in the frequency domain can be overcome by a correlation technique [153]. Active vibration control by a combination of feedback and feedforward control is achieved with a neural network that models the structural dynamics by following the state variables [154]. The numerical complexity of the error path modelling ("C modelling") in multichannel systems using the filtered-x LMS algorithm can be dramatically reduced by replacing the C model with a simple delay and a delayed Hermitian transpose of the C model introduced in the error path [155].

An adaptive feedforward single channel ANC system with feedback cancellation and online modelling of both the error path and the feedback path is described in [156].

A method of radio transmission path analysis for telephone lines is disclosed in [157], in particular for recognizing line echoes; it helps to decide whether or not correction means (echo cancelers etc.) have to be applied; the algorithm is based upon a frequency-domain adaptive LMS filter.

The spatial and spectral discrimination of two speech sources is possible by a crosscorrelation technique applied to the output signals of two microphones, and adaptive filtering such as to minimize the discrimination function [158, 159]. A PC-oriented versatile ANC and AVC unit with graphical user interface is presented in [160] which provides application-specific solutions (feedforward, feedback, filtered-U algorithms) without writing program codes.

An adaptive multichannel acoustic echo canceler for telephone conference and hands-free telephone systems is disclosed in [161] and [162], applying cross-correlation techniques.

The problem of slow asymptotic convergence of the LMS algorithm, i. e. the slowing improvement of filter performance near the optimum, is addressed in [163]; since theoretical and experimental evidence has been found that the slowing is associated with concentration of error energy at frequencies near the band edges of the filter, narrowing of the filter bandwidth could be shown to speed up the filter convergence.

In [164] a method is described of speeding up the performance of an adaptive controller by shortening the filter length. The implementation of a multichannel MIMO system for complex sound fields with multiple digital signal processors and a bus or ring system is outlined in [165]. The permanent error path modelling does not necessarily require an external test signal: in [166] a technique is presented by which the test signal can be obtained from the error signal by phase decorrelation. A transform domain multichannel system with fixed prefilters and provisions for constraining the output in certain frequency bands is disclosed in [167].

A combined frequency and time domain algorithm for simultaneous background noise reduction and echo cancellation is presented in [168], in particular for improved speech transmission with hands-free telephones.

A rather theoretical patent [169] deals with the problem of generalized noise cancellation in a communication channel where different noise components are correlated.

1995: A multichannel adaptive canceler for tonal noise which avoids overparameterization and accounts for phase shifts or delays is described in [170]. A closely related patent presents an adaptive method of limiting the actuator output to the linear range by a back-projection technique [171]. Since the convergence of the LMS algorithm is often slow, the application of a Newton/LMS algorithm is suggested in [172], implementing a fast inversion of the input signal autocorrelation matrix. Adaptive filters with very fast-converging algorithms cannot be assumed time-invariant and therefore violate the LTI assumption of linear system theory. As a consequence, a fast adaptive filter is not interchangeable with the error path model, precluding the application of the conventional filtered-x structure which would lead to serious stability problems. A solution is the separation of filter function and filter update, a concept termed FASPIS (fast adaptive secondary path integration scheme) in a journal publication [173]; this concept has been reinvented in [174]. Noise suppression in communication channels by applying a Wiener filter often suffers from "musical noise" which can be avoided by a spectral estimation procedure as described in [175].

The patent application [176] repeats, in a simplified form, the former patent [54], an adaptive feedforward controller with explicit feedback cancellation and an IIR main canceling filter, however including a feedback version and a two-channel system. The same inventors propose the insertion of an equalizing filter, realized as linear predictor [177]. Also, [178] is essentially a re-invention of [54], including on-line modelling of feedback path and error path. Adaptive feedforward control with the filtered-x LMS algorithm including gain control, interface delay and decimation or interpolation filters is the subject of [179]. A pipelined IIR filter, consisting of a non-adaptive and an adaptive section is presented in [180], including a thorough mathematical treatment.

Overload prevention of the control loudspeaker of an ANC system can be optimized by spectrally shaped power output limitation; in [181] is described how this is achieved with a "spectral leak," i. e., a frequency-dependent leakage factor. A similar concept is outlined in [182]. Multiple source separation from an equal number of sensor signals with unknown contributions of all sources ("blind separation") is possible by adaptive nonlinear processing algorithms [183], [184].

Principles of adaptive interference canceling in the case of highly nonstationary disturbances are outlined in [185], applied to radio transmission systems with rapid tracking control of center frequency and bandwidth of the interfering signal.

An improved algorithm for adaptive noise canceling is disclosed in a series of patents [186]–[189], providing two adaptive filters and variable step size to reduce both convergence time and final residual error.

A frequency-domain algorithm for multichannel ANC and AVC is disclosed in [190], calculating the filter coefficients from cross-spectral density matrices, the estimated plant transfer function, and singular value decomposition to account for possible ill-conditioning.

1996: The problem of channel decoupling in multichannel feedback control of repetitive noise has been solved by a matrix operation so that a set of single channel controllers remains [191]. Enhancing the reference signal in a feedforward ANC or AVC system by an adaptive line enhancer is the subject of [192]. A modified multichannel adaptive filtered-x LMS algorithm is outlined in [193]; by inserting a filter in the update input differing from the error path transfer function, the system is said to reduce complexity for, e.g., ANC in three-dimensional enclosed spaces.

Noise reduction for speech or music signals can be time- and cost-effectively improved by separation into the predictable part and the prediction error, both parts being adaptively gain-controlled and then combined in the improved output signal [194].

In order to reduce the computational power requirement, a non-adaptive feedback controller with fixed-filter model reference control is proposed in [195] for ANC systems in enclosures. The stability problem occurring from the dead time in the room transfer function is solved by a Padé approximation, and robustness is achieved by adjusting a stability factor. Variations of the transfer function are accounted for by a preregistered perturbation function.

1997: Apparently a re-invention of [118] and [146] is [196], presenting error signal filtering as an alternative to the reference signal filtering of the filtered-x LMS algorithm, providing reduced numerical complexity. Convergence problems of the filtered-x and delayed-x LMS algorithms can occur when the system to be controlled exhibits sharp resonances and the input signal is periodic with rapid frequency sweep; a stabilizing algorithm modification is presented in [197]. In order to improve automatic speech recognition, in [198] a method is suggested to remove convolution noise components, such as introduced by microphone characteristics, applying a cepstrum filtering process. A modified LMS algorithm/adaptive FIR filter device for ANC in hands-free telephones is suggested in [199], resulting in power saving control as compared to previous systems; the cancellation concentrates on frequencies where the noise is particularly disturbing.

1998: An acoustic and line echo cancellation and noise suppression device is described in [200], providing speech enhancement for teleconference set-ups etc., adapting simultaneously for both transmit and receive path. A combined feedforward/feedback adaptive ANC system with three digital filters and two coefficient update units is disclosed in [201, 202]. A method for acoustic system identification in a noisy environment is disclosed in [203]; in order to make the broadband test signal loud enough and yet inaudible, spectral shaping is applied utilizing the psychoacoustic phenomenon of masking.

1999: Supplementing a stereo loudspeaker set-up by a third loudspeaker in front of and nearer to the listener, crosstalk cancellation with delay lines, high-pass and low-pass filters widens the range of permitted head movement without destroying the effect of virtual sound source localization [204]. The convergence speed of, e. g., an echo canceler is higher with subband filtering than with the LMS or normalized LMS algorithm; in [205] it is claimed that a 3 dB overlap of adjacent bands reduces aliasing effects which otherwise also slow down convergence. Overall modelling of a single channel or multichannel adaptive feedforward ANC system is disclosed in [206] and [207], using the filtered-x or filtered-U LMS algorithms and initial system identification with two different test control models; continuous error path modelling can be replaced with occasional updates if the error path changes only slowly.

A digital modulation technique for canceling acoustic feedback in public address systems, hands-free telephones etc. is presented in [208]: the sound reaching the microphone is converted into an inaudible, digitally modulated signal which is combined with the traditional microphone signal; in case of acoustic feedback, the microphone receives the loudspeaker signal containing the inaudible component which now can be used to subtract the feedback signal from the microphone signal. This is a digital analogue to former patents applying analog modulation [209], [210].

2000: The patent application [211] claims to present a novel ANC system avoiding the stability problems of feedback controllers and the convergence problems of adaptive feedforward control by application of a fixed digital filter feedforward system to generate the cancellation signal, however ignoring the problems of time-varying parameters. A controller providing ANC or AVC for complex nonlinear multi component systems (aircraft, helicopters, ships) is presented in [212] and [213], using a neural network to model the systems and another neural net to calculate the control signal.

2001: The time delay in digital signal processing often presents problems. It can be reduced by applying a sigma-delta converter instead of the usual digital-to-analog converter with the necessarily delaying antialiasing filter [214].

3. ANC IN DUCTS AND MUFFLERS

3.1. Ducts

The active cancellation of one-dimensional sound fields in ducts has for the first time been proposed by Lueg [7]. More detailed, still rather early patents are those of Parramore (1970) [215], Swinbanks [216] and Wanke [217], both in 1972, and in 1974, of Lawson-Tancred [218] and Walker [219]. The Jessel group has applied for a patent [220], describing an adaptive feedforward system with a tripole as secondary source to avoid acoustic feedback and standing waves in the "upstream" direction. Similarly, Coxon and Leventhall have described in 1976 the "Chelsea Dipole," a means of feedback cancellation to prevent howling in a feedforward control set-up [221]. Swinbanks has proposed the application of phased loudspeaker arrays as unidirectional transmitters [222], and a filter bank system for multi frequency signals, including adaptive control with analog or digital electronics [223]. Bose has described a feedback set-up for low-frequency ANC in exhaust ducts [224]; a modern version is disclosed in [225], including several modifications (see Section 4, first paragraph). An active silencer duct with octagonal instead of circular cross-section is proposed in [226], for ease of loudspeaker attachment.

Ross [227] and Swinbanks [228] have described adaptive active duct silencers with digital control in a system identification configuration. In [229] an electroacoustical system is outlined which can either compensate for a (reverberant) room response in high quality sound field reproduction (by prefiltering with the inverse room transfer function), or serve as an adaptive feedforward ANC system for ducts with a two-loudspeaker dipole source, thereby avoiding acoustic feedback. Broadband "downstream" cancellation without "upstream" reflection is obtained by either providing the feedforward analog amplifier with a digital negative feedback loop [230], or a cascade structure of secondary sources as outlined in [231]. Also described in [230] is a demonstration installation of the ANC system, with 72 large loudspeakers around the upper end of the 3.25-m diameter chimney stack of a gas turbine, canceling the narrowband rumbling noise between 20 and 50 Hz. A purely mechanical noise canceling device for exhaust ducts by counter-oscillating disks in the main duct and a parallel cancellation duct is presented in [232], similar in principle to those of Coanda [5], [6], with doubtful effect since no precautions are taken to guarantee amplitude and phase match to the primary sound. A feedback ANC system in analog electronics with howling prevention by gain control is described in [233].

Technical applications of the cancellation of *broadband* duct noise became possible after the introduction of digital adaptive signal processing, including adaptive feedback cancellation. Some of the "algorithm" patents cited in Section 2 are related to duct silencers: [28, 30, 31, 35, 37, 40, 43, 54, 55, 71, 72, 77, 80, 81, 100, 108, 110, 119, 130, 131, 145, 181, 182]. Active duct silencers with digital control are also proposed in the Japanese patents [234] and [235]. In order to reduce noise pick-up by the wiring between ANC components, the insertion of optical modems and optical fibers between the microphones, loudspeaker amplifiers and the signal processor is proposed in [236]. Hybrid (passive and active) systems are disclosed in [237, 238], and an adaptive feedforward active duct silencer employing the filtered-x LMS algorithm with feedback compensation and an auxiliary noise source for feedback and error path modelling in [239].

An adaptive feedforward ANC system where the active elements are arranged in a cigar-shaped central piece in a circular ventilation duct is described in [240]. Another adaptive feedforward ANC system for duct noise is disclosed in [241] where a two-stage adaptation procedure eliminates possible distortion by noise entering the duct from the downstream side. An improved version of the

Swinbanks dipole system for ANC in ducts is presented in [242]. A hybrid sound attenuator is described in [243], comprising resonance absorbers (possibly with active tuning), porous absorbers (possibly with active backing) for the high-frequency range, and an adaptive ANC system with reference microphone(s), canceling loudspeaker(s) and error microphone(s) for the low-frequency range. An adaptive feedforward noise control system for liquid-filled pipes (where the sound propagation velocity depends on the stiffness of the pipe wall) is described in [244]. Further feedforward systems for canceling duct noise in air conditioners are disclosed in [245], [246], [247] and [248]. An actively controlled resonance absorber for automobile exhaust mufflers is described in [249].

An active noise canceling device for application to one-dimensional sound propagating in a duct consists of an array of resonance absorbers, driven as a phased array from a single loudspeaker through delay lines of different lengths [250].

A system for collocated feedback control for ANC or AVC in one-dimensional systems is presented in [251] where particularly the phase shift problem is addressed and solved by adaptive digital nonlinear filtering with a reset logic.

The problems of canceling *higher-order modes* in ducts above the cut-on frequency of the first transverse mode are addressed in [252]–[256]. These problems can be avoided by lengthwise partitioning of the duct and providing separate ANC systems for each cell [257]–[260]. To save installation space in a lengthwise partitioned flow duct, it is proposed in [261] to use porous absorber plates as partition walls and to insert the microphones and loudspeakers for an adaptive feedforward ANC system flush into these partitions.

Microperforated plates are proposed as passive sound absorbers in flow ducts; they can, in particular, attenuate cross modes which otherwise impair the performance of active absorbers mounted at a side wall [262]. Fluid-borne sound in pipes (hydraulics etc.) can be cancelled by feedback controlled piezoelectric actuators mounted at the pipe wall [263].

3.2. Mufflers

Patents on the application of ANC to mufflers of internal combustion engines have been applied for since many years. Loudspeakers mounted to the exhaust tail pipe are proposed in [264], but with only vague ideas of how to feed them. A combined electronic phase inversion and geometrical adjustment of the cancellation loudspeaker in a side branch is proposed in [265]. Chaplin has proposed to install, near the tailpipe orifice, a feedback-controlled microphone/loudspeaker system which acts as a local active sound absorber [35]. A feedback-controlled loudspeaker attached to the side wall of an air intake or exhaust pipe is disclosed in [266]. A valve-controlled bypass, splitting the gas flow in order to provide noise canceling by interference, is disclosed in [267] and [268]. A typical control strategy uses synchronization signals from the engine, forms the canceling signal by waveform synthesis, and radiates the canceling sound from one or more loudspeakers which are mounted near the tail pipe [269]–[273]. A divergence monitoring device is disclosed in [274] and [275], securing stable operation of an active muffler. Adaptive feedforward control with the error microphone and the loudspeaker in a silencer space, including a time delay unit to compensate for the propagation path between error microphone and loudspeaker is proposed in [276]. A similar device with two microphones in the silencer space is disclosed in [277], and with two loudspeakers in [278]. A passive muffler for vehicle exhausts is disclosed in [279], diverting the sound wave into a multitude of partially reflected waves which destructively interfere with each other. Further patents on mufflers with adaptive feedforward control are [280]–[289]. Feedback active mufflers are disclosed in [290] and [291], the last one presenting also detailed descriptions of the mechanical design.

Emphasis on the optimization of engine performance by active control of inlet and/or outlet pressure fluctuations is laid in [292]. Mufflers combining tuned passive resonators and active cancellation by loudspeakers in feedback configuration are disclosed in [293]. A two-stage active muffler is presented in [294]: the crest factor of the pressure pulses is reduced by a pneumatic control device, e. g., a valve-controlled conduit from the exhaust pipe to the intake manifold so that the pressure peaks in the pipe are sucked away by the intake underpressure; the remaining low-amplitude noise is cancelled by a common ANC system with a downsized amplifier and loudspeaker.

The technology of generating air pressure pulses in synchronism with the firing frequency of internal combustion engines is also applied for by conveying charge air to the intake manifold, enabling active engine tuning by variation of pulse frequency, amplitude and phase in order to adapt the engine power to the momentary demand [295]. A further development provides two loudspeakers, one near the plenum to serve as an adjustable impedance for the pulse reflections, the other one near the air intake to reduce the impulsive noise radiated to the outside [296]. An adaptive-passive reactive muffler with feedback position control of an internal plate with attached pipe, dividing the muffler chamber into two chambers, is proposed in [297].

Many ideas have been disclosed on the problem of heat protection for the loudspeakers and on special loudspeaker arrangements for exhaust pipes [298]–[335]. Actively tuned Helmholtz resonators for noise reduction in ducts and mufflers are the subject of [336]–[341]. In [342] an active absorber in a side branch to an exhaust duct is proposed, realized as a feedback-controlled loudspeaker so as to optimally remove sound energy from the duct by impedance matching. Variable muffler geometry providing optimum engine efficiency (by backpressure reduction) is the subject of [343].

Other actuators than loudspeakers have also been proposed for active duct noise control and mufflers: hollow piezoceramic cylinders mounted at the inner duct wall [344] or pipes carrying flow with active sections made of piezoelectric films [345], and oscillating flaps or valves which modulate the gas flow in the exhaust pipe [346]–[350] (the last one with a Venturi tube in order to alleviate the flap design). Related is a patent on backpressure braking control by an oscillating valve for commercial diesel engine vehicles [351], and also a construction where the exhaust gas flows through an expansion chamber in which a baffle plate is vibrated opposite to the primary tube end in synchronism with the flow pulsations, thus smoothing the gas flow [352]. Injection of small amounts of water which evaporates in the hot gas and so causes smoother flow has also been proposed [353].

A series of General Motors patents aim at a combination of active control of intake and exhaust noise with active engine mounts [354]–[357]; [354] describes a method of overload prevention of the adaptive filters. A physically sophisticated approach is outlined in [358], a hybrid silencer for ventilation ducts realizing a theoretical optimum of the acoustic wall impedance (which is modified by the gas flow); the technical realization of this concept is lacking, however, from causality constraints. A more realistic version is presented in [225]. An exhaust muffler with feedback control of loudspeakers to provide an acoustic short circuit near the tail pipe is described in [359]. A muffler with tracking control and desired-signal recovery from the error signal and adaptation by the LMS algorithm is disclosed in [360, 361]. Active duct silencers with the control parameters taken from a look-up table are outlined in [362]–[365].

An active muffler with adaptive feedback control in cascade structure is presented in [366], and one with tracking control and provisions to prevent loudspeaker overload in [367]. Duct silencers with feedforward control and microphone pairs as directional input sensors to avoid feedback instability are outlined in [368] and [369], both obviously being re-inventions of [370]. An adaptive feedforward ANC vehicle exhaust system can be combined with an engine diagnostic system, monitoring misfires etc., which employs a neural network pattern classifier [371]. An exhaust muffler with indirect error sensing by error microphones placed in the primary and secondary sound wave guides is presented in [372]. An exhaust silencer with sound quality design to meet subjective preference is proposed in [131].

In order to reduce the exhaust noise of aircraft jet engines during ground testing, the exhaust flow can be guided through a diverging conduit which is lined with a passive damper for the high-frequency noise, while low-frequency components are cancelled by a multichannel ANC system with, e. g., eight loudspeakers [373]. The problem of turbulence noise in ducts with strong air flow is addressed in [374]; the coherence between reference and error microphone responses in a common adaptive feedforward controller is improved by passive flow straightening with porous plates or the like.

ANC for canceling air intake noise in vehicle interior space is disclosed in [375], the canceling signal being synthesized from engine control parameters. In a further development [376], an active silencer to reduce the engine air intake noise of a vehicle is provided with a divergence monitor to switch off the canceling signal in case of howling onset. A similar system is disclosed in [377], with the additional option of creating a sound indicative of the engine's operational state; thus the vehicle compartment can either be silenced or provided with a desired sound.

To reduce aircraft engine inlet noise, flush mounted panels in the nacelle wall are driven piezoelectrically in an adaptive feedforward system to cancel the blade passage frequency and first harmonics [378]; the efficiency of the radiators is increased by tuning the actuators to resonance at the desired frequencies, employing stiffness control by pressurizing the actuator housing. Active wall treatments are also suggested in [379] and [380] where the actuators are driven so that their acoustic input impedance matches the optimum.

Axial fans in wide ducts generate rotating sound fields ("spinning modes"). Their cancellation is possible by peripheral annular loudspeaker arrays which are fed in synchronism with the propeller tip rotation [381]. According to [382] the tonal noise radiated from a jet engine, due to circumferential modes in the duct, can be sensed by a circumferential microphone array and cancelled by controlling flow distortions, either the orifices of an array of nozzles, or the protrusion amplitude of rods pushed into the gas stream. In [383] several rings of microphone and loudspeaker arrays in the circular outlet flow ducts of turbomachines are proposed for the active cancellation of circumferential (spinning) acoustic modes, utilizing the results of a thorough analytical and numerical analysis of the noise and antinoise generating mechanisms.

In [384] and [385] are disclosed feedback and adaptive feedforward ANC system for the air intake noise of an internal combustion engine, being placed centrally in a widened section of the intake duct. A particularly energy-saving ANC muffler for vehicles with internal-combustion engines is described in [386].

As a passive alternative to ANC mufflers, cross passages between regions of the exhaust and intake manifolds provide noise cancellation by interference [387].

The cancellation of higher-order modes in industrial exhaust stacks is possible, according to [388], by a multichannel adaptive feedforward ANC system.

4. ANC IN INTERIOR SPACES

4.1. Room Acoustics

Many patents are related to local or global control of sound in interior spaces such as vehicles and aircraft, some also to room acoustics in general. Olson [8] was the first to construct a loudspeaker with a microphone in front and feedback control to provide an active absorber. He suggested applications as local silencer or to suppress room resonances. Modern versions of this concept are given in [389] with adaptive digital control for time-varying room response and multichannel control for large enclosures or high modal densities, in [225] for applications to ventilation ducts etc., and in [390] as a compact unit for both active modal control of room resonances and, by an additional audio input, for sound reproduction with room-specific prefiltering to avoid distortions like coloration by room resonances.

For the equalization of the room response, active control by loudspeakers with motional feedback for arbitrary and frequency-dependent acoustic input impedance has been proposed [391], and room response control by loudspeakers in the corners [392]. The cancellation of periodic disturbances in the presence of other periodic noise is outlined in [393], the interfering disturbance being eliminated by a second input, based on the principle of adaptive noise canceling. An actively controlled Helmholtz resonator is disclosed in [394] where a PID-controlled loudspeaker is placed in the resonator volume to simulate a larger volume and thereby providing enhanced low-frequency absorption. Uncoherent active sound field control for spatial equalization and reverberation enhancement or adjustment is outlined in [395] and [396].

4.2. Local Control in Rooms

Local noise control for persons seated in a wing chair (sometimes called a *silent seat* or *quiet seat*), with loudspeakers mounted in the wings, has been disclosed in [111], [397]–[400], the last one using loudspeakers which are open-backed, so acting as dipole radiators which serve as noise cancelers in the nearfield without giving rise to enhanced noise in the farfield. Such systems are also the subject of [401], intended for applications to passenger seats in trains etc., employing adaptive feedforward control with the filtered-x algorithm and IIR filters, and crosstalk cancellation to avoid disturbance by the ANC system of the neighboring seat. A similar wing chair with microphones and loudspeakers behind the passenger head in a car or aircraft is disclosed in [402], claiming that the mechanical design is such that the transfer functions are independent of the passenger head position. A quiet seat with hinged wings is disclosed in [403] so that the distance between the loudspeakers and the ears can be varied to adjust the efficiency of the (feedback) ANC system. A personal noise cancellation system with combined feedback and adaptive feedforward control is disclosed in [404], providing good performance for both tonal and broadband sound, creating a zone of silence around the error microphones.

Active local control of machine noise etc. is proposed in [405]–[409], cancellation at a movable point by motion tracking and a device which keeps the distance to the secondary source constant [410], or with ultrasonic ranging in [411, 412, 413], and the active cancellation of sound entering a room through a relatively small area (e. g., a window) in a subspace of the room by a microphone array and a loudspeaker array [414]. Noise cancellation in a "zone of quiet" by placing a loudspeaker array in front of the noise source is proposed in [415]; the adaptive digital feedforward system includes means for equalization, echo cancellation and feedback cancellation. Local silencing in a room by adaptive feedforward control with remote error sensing is proposed in [416]; two phased arrays of error microphones are installed on different walls and steered such as to intersect in the region to be quieted.

The cancellation of disturbing noise in domestic rooms from electroacoustic equipment of neighbors, transmitted through the walls, is addressed in [417], providing an adaptive feedforward multichannel ANC system with wireless reference signal transmission either from the disturbing sound source, or, e. g. in case of loud TV sound, from the own antenna tuned to the same program.

Synchrophasing (see Section 4.4) has been proposed to reduce the (infra)sound emission from groups of vibratory feeders and similar equipment in factory spaces by operating adjacent machines in antiphase [418]. Twin centrifugal fans can similarly be synchronized in antiphase to reduce their noise emission [419].

An application of actively controlled loudspeakers to provide an acoustic shadow [420] is acoustically questionable (an idea similar to that of Coanda [6]). Questionable is also the active cancellation of *snoring noise*, claimed in [421] without accounting for wall reflections (not to mention the installations in immediate neighborhood of the sleeper's head), or [422] where the canceling sound is to be taken from a data storage, assuming exact reproducibility of typical snoring sounds, but no provisions are made for, e. g., phase adjustment. An increasingly unpleasant sound created from the snoring noise by modulation techniques [423] is more likely to be successful (if presented to the snorer only). Active cancellation of snoring noise at the ears of a bed partner is also disclosed in [424], the same technology being proposed for silent seats and noisy hotel rooms.

A different field where the same technology as for local ANC is applied is magnetic field cancellation at the location of sensitive equipment such as a high-resolution electron microscopes [425]; three pairs of Helmholtz coils installed along the room edges are feedback-controlled to compensate for externally generated magnetic fields at a sensor placed near the instrument. A similar patent is [426] according to which both the magnetic and electric component of the electromagnetic power line field in rooms can be cancelled in a feedback control loop, the electric cancellation field being generated by large area electrodes along the walls.

4.3. Audio Reproduction in Rooms

In order to adapt stereo loudspeaker systems to the acoustic conditions in the room where they are installed, an automatic equalization system is presented in [427]. Noise suppression in domestic audio systems by adaptive noise canceling is proposed in [428]. Electroacoustic sound reproduction in a room is also the subject of [429] where low-frequency resonances are actively cancelled as in [8], but early reflections and reverberation are enhanced by an "ambience generator," so providing some sound quality design. Audio recording restoration for, e. g., motion picture film soundtracks by multiband digital filtering with online adaptation of the spectral band gains is disclosed in [430], providing both equalization and noise suppression. Stereo reproduction of (classical) music played by an orchestra with spot microphones (to enhance voice or quiet instruments) often suffers from interference effects due to the different acoustic path lengths to the microphones; an adaptively controlled delay in the spot microphone signal path cares for maximum correlation of the spot microphone and the stereo microphone pair and removes the interference disturbance [431].

Stereophonic sound field reproduction with a wider listening space is generally possible by the two conventional stereo loudspeakers when head-related crosstalk cancellation is applied (see Section 2, 2nd paragraph). Besides the original patent [17], many more inventions are based on this concept, claiming to create virtual sound sources in any direction and at any distance, e. g., [432]–[440]. The same effect is said to be achieved by two full-range loudspeakers in each box, fed with sum and difference signals of the left and right channels [441], or by a method disclosed in [442, 443], involving variable delays, or [444], claiming to reproduce stereophonic recordings with a compact two-loudspeaker source and complementary feeding so that the stereophonic impression is experienced in a wider angular range than usual. Sound field reproduction with stereophonic signals and cross-coupling through filter banks and phase shifters can, according to [445], also produce true three-dimensional illusion. A transportable sound reproduction system with nearfield loudspeakers positioned very near to the listener is said to create, from binaural records, a more realistic three-dimensional illusion than with headphones or conventional stereo loudspeakers [446]. In [447], a system is proposed applying, among others, feedback control.

A sophisticated method for generating virtual (also moving) sound sources from two stereo loudspeakers is disclosed in [448]. Almost an overview article on nearly all aspects of large area stereo audio reproduction with crosstalk cancellation and head-related transfer functions is presented in [449]. A compact two-loudspeaker box for stereophonic multichannel reproduction is provided in [450], suggesting a baffle projecting forward from the box between the two speakers, aiming at prevention of an acoustic short-circuit; sophisticated digital filtering provides interaural crosstalk cancellation and hence large area stereophony. Another method of creating surround sound, again with the two conventionally located stereo loudspeakers only, is described in [451], connecting the loudspeakers by phase-shift networks to function as a gradient source and minimizing the direct sound component at the listener's ears. Enhanced spatial effects can also be created from mono or stereo inputs by a combination of delay and filtered cross-feeding to the stereo loudspeakers [452]. An advanced filter technique for steering perceived sound source locations from stereophonic loudspeaker reproduction into arbitrary directions employs, besides cross-talk cancellation and head-related transfer functions, a new technique for interpolating between head-related transfer functions [453, 454]. Another advanced stereophonic sound image control system is presented in [455]–[457], providing means to move a virtual sound image left/right, near/far, and up/down; this is achieved by digital filtering including delays, gain control, crosstalk cancellation, and generalized head-related transfer functions. A three-loudspeaker system with improved crosstalk cancellation is described in [204], permitting head movement in a wider range of positions than with the usual two-loudspeaker arrangement.

A sound field expansion system with separate bass and treble control is presented in [458]. Stereo image expansion is typically associated with mid-frequency coloration, an effect which is avoided by systems presented in [459] and [460], employing sum and difference signals, a mono/stereo estimator whose output is used to adjust gains of various filters to realize the head-related transfer function and crosstalk cancellation.

Artificial reverberation of a stereophonic sound field reproduction system provides enhanced subjective lateral spread by filtering and cross-feeding (inverted) signals between right and left channels [461]. In [462], the loudspeaker output is monitored by an auxiliary microphone, and an adaptive feedback system controls a precompensation filter to mimic the inverse loudspeaker transfer function, thereby compensating for loudpeaker distortions.

A series of patents [463]–[469] describe an efficient, flexible *surround sound* coding scheme claiming to be superior to former matrix systems; the method makes use of spatial and spectral masking phenomena and requires less transmission bandwidth than former systems. A method for enlarging the sensed sound field and creating a feeling of spaciousness without affecting sound source localization is disclosed in [470], employing multi-loudspeaker reproduction, delay units, crosstalk cancellation, phase control, and reflected sound simulation. A five or more channel system for stereophonic sound field reproduction in rooms is described in [471] where a special method of signal processing provides a much larger space for good listening.

A multichannel surround sound system with five full-range loudspeakers and a subwoofer applies dynamic electronic processing to improve the sound field reproduction by creating a more diffuse sound field [472]. A four-dimensional audio system is outlined in [473], claiming to maximize depth, width, and perceived directionality of the sound field. In the continuation of this patent, a portable collapsible seat is disclosed with integrated five-loudspeaker audio system to create a virtual reality environment [474]. A sequence of patents [475]–[478] address active matrix sound field reproduction, converting stereophony to surround sound. Surround sound generation from two stereo channels is also claimed in [479], cleverly mixing the two primary channels, including crosstalk cancellation, filtering and phase-shifts. Somehow the opposite procedure, namely to condense the, e. g., five surround sound channels into two conventional stereo signals is sometimes desired; a method to achieve this is described in [480, 481].

If the surround sound loudspeakers cannot be placed according to the recommended standard, the patent [482] can help by relocating the perceived sound source direction, applying head-related transfer functions and cross-talk cancellation. Another fairly complex method of multichannel sound field reproduction is disclosed in [483], providing also spatial equalization if the loudspeakers cannot be placed optimally.

An improved audio reproduction method by headphones is described in considerable detail in [484, 485, 486], providing, among others, sensing and compensation for head movements. A "direct" approach to multichannel surround sound reproduction by a headset is claimed in [487]: each earcup carries a plurality of miniature loudspeakers along its hemispherical surface "to simulate the directional orientation of the sound as perceived by the listener."

Stereophonic sound field reproduction in cars where the loudspeaker placement is dictated by constructional requirements can be improved by cross-coupling the left and right channels, providing fluctuating coherence [488]. A novel system for spatial enhancement and improved bass reproduction has been developed for small and closely-spaced stereo loudspeakers (e. g., in portable TVs), applying differential amplification, filtering and equalization [489]. A similar cross-feeding technique is proposed in [490] for the spatial enhancement of stereophonic reproduction.

4.4. Propeller Aircraft and Helicopters Cabins

Interior noise suppression is particularly a problem with propeller aircraft and helicopters. Approaches with multichannel adaptive feedforward control or tracking control (with synchronization input from the engine) and loudspeakers as secondary sources are outlined in [491]–[501], or with shakers or piezoceramic patches acting on the fuselage (the ASAC technique, see Section 9) in [502, 503]. Synchrophasing of the left and right propeller, so that the vortex threads separating from the propeller blade tips hit the fuselage out of phase, is the subject of [504]–[510]. In-cabin noise in helicopters, caused by vibration input from the main gearbox, can be suppressed by active stiffening of transmission beams, thereby suppressing resonance excitation also at high frequencies [511], or by applying cancellation forces to the struts connecting the gearbox and the helicopter cabin, with a microphone array as error sensors in the cabin [512]. Synchrophasing can be optimized with respect to balancing the cabin noise so that there are no "hot" seats with high noise level [513]. Loudspeakers, shakers and synchrophasing are also suggested in [514] for the cancellation of periodic noise in propeller aircraft and helicopter cabins. Noise and vibration reduction in a propeller aircraft fuselage by active engine mounts and actively controlled dynamic absorbers is outlined in [515], with special emphasis on a pulse modulation technique to reduce heat dissipation in the actuators. A multichannel adaptive control system for local cancellation of repetitive noise at the head positions of aircraft passengers is described in [516], using matrices of transfer functions from the canceling loudspeakers to arrays of reference and error sensors.

4.5. Jet Aircraft Cabins

ANC for repetitive noise in the interior of jet aircraft is the subject of [517] where a multichannel tracking controller with a frequency domain algorithm is applied. Interior noise in jet engine aircraft can be caused by engine imbalance. A method of in-flight condition monitoring and imbalance control is outlined in [518]. Broadband adaptive feedforward control in aircraft and car compartments with multichannel systems is outlined in [153, 519]. The latter patent is accompanied by [520] where shakers acting on the fuselage for low-frequency control are combined with loudspeakers mounted in the headrests for high-frequency noise. Broadband adaptive multichannel feedforward ANC for aircraft cabins can, according to [521], be designed with less complexity due to typical partial channel decoupling. Active mass dampers attached to the structure connecting the aircraft engines to the frame and fuselage are the subject of [522], providing reduction of repetitive vibration and noise in the passenger cabin by a variety of possible structural realizations and control strategies. A different approach to cancel jet engine noise is suggested in [523]: the canceling sound waves are generated in the combustion chamber by exciting plasma oscillations with electric fields applied to electrodes inserted into the plasma.

4.6. In-Vehicle Sound Field Control

Many car manufacturers and associated companies are investigating the possibilities of ANC in vehicle cabins. A technically solved problem is the cancellation of the "boom," an often annoying resonance of the air volume excited by an inherent unbalance of 4-cylinder internal-combustion engines. The Nissan car "Bluebird" has been sold in Japan for some years with an optional active noise control system. Many patents in this field (also by other manufacturers) can be found [56, 67, 88, 496, 497, 116, 117, 118, 135], [524]–[584]. The usual approach is tracking control with the engine rotation frequency as synchronization input, error microphones near the passengers' heads, and using the existing on-board loudspeakers as control sources. Since the engine rotation frequency varies over a large range between idle and full speed, the efficiency of the digital signal processing can be improved by applying a variable sampling frequency [109]. The computational need of tracking control can be reduced by taking the adaptive filter coefficients from a look-up table [585]. Cancellation of engine noise entering the vehicle cabin through the ventilation ducts is the subject of [586] and [587], including stability precautions by switching off the cancellation signal when certain system conditions occur. A special mechanical support for the error microphone next to the ANC loudspeaker is disclosed in [588].

If no synchronization signal can be taken directly from the engine, the alternator's a.c. output will provide a frequency proportional to the engine rotation frequency [589], [590]. In [526] is suggested a system without error microphones, taking the filter parameters from a look-up table according to the ride status of the car. A similar system is proposed in [591] where the information on the ride status of the car is monitored, not only to select the cancellation signal from the data storage, but also for fault detection. Following [528], the error microphones can be placed in the headrests. Certain problems with seat-mounted microphones can be avoided by a "virtual microphone," realized by the weighted sum of the output signals from two or more microphones placed around the head position [532]. As a further development, [592] combines it with tracking the position of the speech source. A feedback controller with microphones placed in Helmholtz resonators which are tuned to the car resonances is disclosed in [529].

In order to improve the performance of a multichannel ANC system for the interior space of a car, crosstalk cancellation has been proposed in [539]. A combined ANC and AVC system for engine-related disturbances in vehicles applies a two-channel filtered-x LMS algorithm to feed a shaker and a loudspeaker, the balancing of both being adjusted according to many parameters, such as engine or vehicle speed, number of passengers, opening of windows, etc. [561]. The geometry of automobile compartments is such that often the fundamental cavity resonance creates an antinode of the sound field at the rear seats, but a node at the front seats; the patent [593] provides a method to spatially equalize the sound field by driving a central rear loudspeaker with an $L + R$ signal after bandpass filtering and phase-shifting. The cancellation of repetitive engine-related noise in a vehicle interior space by actively vibrating the compartment panels is disclosed in [594] (see also Section 9). Actively vibrating the window panes of a car by piezo actuators is suggested in [595] to reduce noise entering the car cabin from outside. An earlier patent [596] proposes a special design of the vehicle understructure so that the floor panels vibrate less in the front region than in the rear, and the phase relation is such that the radiated sound interferes destructively in the head area of the front passengers.

In [597] an active system is proposed which either acts as an adaptive feedback-controlled multichannel ANC system for a vehicle cabin (with fuzzy control), or as an alarm system responding to unauthorized intrusion into the vehicle, based on ultrasonic surveillance.

The active cancellation of air intake noise of an internal combustion engine is the subject of [598], providing adaptive tracking control of engine-related repetitive noise; a piezoelectric loudspeaker is mounted in a side branch of the air intake pipe, and special attention is paid to the cancellation of half-integer harmonics of the engine rotation speed which are said to be particularly annoying.

A series of Siemens (Canada) patents deal with ANC for engine-related repetitive noise cancellation in the passenger cabins where the loudspeaker is mounted under the engine hood and acts upon the air induction system of the car. An (adaptive) feedforward ANC system is disclosed in [385] where the loudspeaker is mounted in the center of the widened air inlet duct mouth so that the air flows around the loudspeaker (see also Section 3). A curious extra facility of the ANC system is proposed in [599] and [600]: the generation of a horn signal by the ANC loudspeaker when the horn button at the steering wheel is pressed. An optimized loudspeaker membrane shape matched to the non-round air duct mouth is disclosed in [601]. An adaptive tracking controller is outlined in [602], communicating several engine-related data to the signal processor (crank position, fuel injection data, ignition data) without or with hardwire connection and interrupting the active noise control when, due to low engine load and hence low noise, no cancellation is required; the decision may be facilitated by transmitting exhaust air temperature and throttle position data. This strategy has been further developed towards sound design in [603] where the loudspeaker is driven in one of two modes, one applying during normal driving and the other one for sportive driving, the decision again depending on engine speed and engine data, and providing either ANC or a "sportive sound." The low-frequency performance of the ANC loudspeaker can be improved, according to [604]: the centrally mounted loudspeaker in the air inlet duct acts on a resonance chamber in front, which is sealed by a sound radiating membrane in the inlet plane, the resonance frequency thereby being lowered as compared to the loudspeaker alone. Alternatively, a loudspeaker horn can be provided [605]. A similar device is claimed to work without microphone and online adaptation [606], where the cancellation signals shall be stored in a memory file as a function of the engine speed, the output signals being modified according to additional input data of throttle position and temperature. A method of mounting the ANC system so that it is protected from the harsh environment under the engine hood is disclosed in [607]. In [608] the problem is addressed that a too perfect ANC system may confuse the driver by no longer hearing the typical engine sound. The controller therefore creates, depending on the operating conditions, start-up sound, idling sound, or driving sound and radiates it into the cabin at an adjustable level. Several methods of selection of the preferred noise cancellation or engine sound profile are outlined in [609]: by a hand-held device such as a cellular phone, a keypad, or a touch screen. A seemingly consequent further development is the creation of a typical door closing sound to improve the user perception of his or her car [610]. According to [611] the air flow in the air intake can be used to cool the ANC processor board. The signal processing method for adaptive feedforward control with online modelling of the transfer function is described in [612]. The combination of an ANC system in the air intake duct and a Helmholtz resonator tuned to $60 \cdots 90$ Hz allows a smaller ANC loudspeaker and less canceling signal power to be applied [613]. A variety of ANC loudspeaker mounting devices is sketched in [614], and a microphone calibration method in [615]. A method for faster adaptive filter convergence is disclosed in [616] by starting with an initial estimate of the error path transfer function. Adaptive tracking control of repetitive engine noise by a frequency-domain technique is outlined in [617], and by an order analysis in [618]. A space saving housing of the ANC loudspeaker is disclosed in [619], combining it with one or two of the fluid reservoirs placed in the engine compartment. A microphone protection system is developed in [620], and an actively tuned Helmholtz resonator in [621].

A particular noise problem in vehicles is addressed in [622]: the noise of a cooling fan for audio or navigation systems can be reduced by reducing the rotation speed of the fan to the minimum value possible without damage risk of the electronics.

A multichannel system for both noise and vibration control in vehicle cabins etc. performs a modal analysis (applying fuzzy control) and cancels the primary vibratory inputs at the engine and car body mounts [623]. A feedback system with a gain-controlled amplifier to avoid feedback instability is disclosed in [624].

Fewer patents than on the cancellation of engine-related repetitive noise exist on the much more complicated problem of canceling *broadband noise* in a vehicle cabin, the "road noise" (caused by the tires rolling over rough road surfaces), wind noise, etc. [73, 91, 133, 519], [625]–[644]. Most of them apply multichannel adaptive feedforward control with the filtered-x algorithm and, again, the on-board loudspeakers as secondary sources. Alternatively, in [630] actively tuned Helmholtz resonators are proposed as frequency-selective absorbers, in [635] a neural network controller driving piezoelectric actuators both for car body vibration isolation and vibration control of the vehicle compartment hull, and in [636] loudspeakers simultaneously acting as sensors so that no microphones are required. Loudspeaker overload can be prevented by power limitation and an "arbitrator" which reduces, if required, the bass output of the audio entertainment system and the low-frequency ANC signal which are most likely to overdrive an amplifier [645]. In [152] a fast recursive algorithm for the adaptive cancellation of road noise in a vehicle cabin is presented, applying accelerometer inputs and acoustical cancellation sources and error microphones. In [646] it is suggested to reduce sound transmission from the outside through the windows by feedback-controlled transparent piezoelectric sensors and actuators glued onto the window glasses. A system with reduced computational complexity is disclosed in [195] (see Section 2, last paragraph). A method of identifying the different sound and vibration sources contributing to vehicle interior noise at a passenger's head is disclosed in [647]. An adaptive feedback control system particularly for heavy offroad vehicles is described in [648], providing an adjustable level of cancellation to meet the individual preferences of the drivers.

A partly unconventional ANC system for vehicle compartments is presented in [649]: loudspeakers and microphones are either mounted in the headrests and a feedback controller provides the signal processing, with an optical sensor tracking the head position and adapting the cancellation signals accordingly. The unconventional alternative suggests to replace the microphones with sort of laser vibrometers to measure the sound-induced skin vibrations near to the ears, or to apply pressure-sensitive paint to the skin next to the ears.

Several patents are related to *sound design* in the cabins of vehicles with internal combustion engines. In [650] a system is proposed to simulate a "sportive" sound also in an average car by deriving from an engine speed (rpm) signal a typical sound spectrum with a synthesizer and radiating it by the loudspeakers of the entertainment system. [651] proposes a sound enhancement system according to the driver's preference, in particular exaggerating typical acceleration-related sound and also vibration, again using a synthesizer, but combined with active cancellation of unwanted noise, and providing an individually controlled mix of noise response with the in-car entertainment program. This concept is extended in [652] to influence the external sound radiation of the bypassing car, too. A similar system as in [650] is suggested in [653], pointing out the possibility of masking unwanted noise components, thus reducing the amount of passive acoustic treatment. Again a similar system is outlined in [654], with combined parametric control (taking information from a lookup table) and feedback control, also arguing with safety aspects. Another patent [655] proposes to transmit simulated engine noise from the front loudspeakers, and simulated exhaust noise from the rear speakers. In order to give the drivers of very silent cars a feeling for the engine performance, it is suggested in [656] to radiate engine-related sound into the passenger compartment, preferably sensed by a microphone in the air intake or exhaust duct. Some recent Siemens patents on vehicle sound design have been mentioned above: [603, 608, 609, 610].

In a sound field with multiple sources in a car, a system can be installed which enables the user to selectively enhance certain desired signals and cancel others by processing the outputs of several microphones [657]. In order to avoid too successful cancellation of engine-related repetitive noise in the passenger cabin of vehicles (making unpleasant high frequency noise audible which has been masked before), an adaptive tracking control system is proposed with a desired-signal input below which the noise level cannot be reduced [658]. A sound generator for application to car cabins provides either an active noise cancellation signal or, in case of rather silent cars, a sound indicative of engine and car speed and acceleration [659]. In [660] it is explicitly assumed that the loudspeaker transfer functions are considered in the sound spectral design, and a certain degree of reverberation may be included, too. [661] claims to achieve the same effect with simpler equipment by radiating from the in-cabin loudspeakers a sound which is derived from the primary engine noise by suppressing undesired frequency bands. Vehicle interior noise caused by vibrations in the hydraulic system can, more simply than with loudspeakers, be reduced by interference with a canceling vibration which is generated by amplitude or pulse modulated servo valves acting on the same hydraulic system [662].

Systems for the mere creation and radiation of vehicle noise have been patented, too. In [663] a system is described which produces, from an accelerator pedal signal, the exhaust noise of a high-performance car for application in drive simulators and games. Supercharge sound including gear train whine of racing cars can be created from the rpm signal [664] and radiated from an ordinary car (or, similarly, a boat) to give it a more impressive appearance. For the more serious purpose of fault or damage detection in cars and other machines, noise synthesizers have been designed in [665] and [666] which selectably produce sounds indicative of various malfunctions; such systems can be used in training courses for technicians, or they can help identify suspicious noises occasionally heard by customers who bring their car to a repair shop where this noise often does not occur.

4.7. Miscellaneous

Noise shielding engine enclosures often suffer from noise radiation through ventilation openings; in [667] a multichannel adaptive feedback control system is developed to reduce the noise transmission. Particularly for application to *personal watercraft*, a vented box as engine enclosure is proposed in

[668, 669], providing multichannel adaptive feedforward control with microphones and loudspeakers to reduce sound radiation from the enclosure walls and the air outlet.

A sound absorbing wall lining for *water tanks* is disclosed in [670]: multiple layers of piezoelectric (e. g., PVDF) material are shunted by active electrical circuitry such as to compensate for reactive components and providing a broadband impedance matching to the incident water-borne sound, thus providing a thin-layer coating for anechoic tanks.

Active cancellation of environmental noise in open *telephone booths* is described in [671].

A curious application of sound field simulation is presented in [672]: as a remedy against *motion sickness*, e. g., for sailors working below deck; an artificial horizon of sound is created in the irregularly moving enclosure by accordingly feeding an array of loudspeakers in response to measured values of ship roll, pitch and yaw.

For the active cancellation of noise from household and business machines, see Section 7 (ANC for Domestic Appliances).

5. ANC IN COMMUNICATION (EXCEPT HEADSETS)

Communication links often suffer from echoes and crosstalk in all domains: in the wireless electromagnetic radio transmission channels, in optical fiber or copper wire connections, and in the acoustic path. To reduce the disturbances, the coherent-active cancellation technology is extensively applied to all three fields. For headsets with ANC see Section 6.1.

5.1. ANC in Radio Links

Some patents are concerned with the cancellation of electromagnetic jamming in multiple subscriber systems. It has been proposed for wireless communication that the desired signal be transmitted, then received by the remote station with transmission path jamming, back-transmitted to the primary station, and – after appropriate filtering and subtraction of the desired signal – be inversely added to the primary signal, thereby (hopefully) providing sort of a disturbance canceling feedback loop or prefilter [673]. Impulsive noise in FM radio receivers in cars which is caused by ignition impulses of the engine can be cancelled by an ANC technology as outlined in [674]. Jamming cancellation in mobile communication links is described in [675], and particularly for radio communication between aircraft and ground station by a feedback control system in [676]. Power line (50 or 60 Hz) interference with correlated audio signals can be removed actively, utilizing the long-term phase stability of the disturbance [677]. The cancellation of co-channel interference in wireless multiple access telephone communication systems is the subject of [678]. Removing multipath propagation interference from communication signals by adaptive beamforming of antenna arrays with automatic gain control is disclosed in [679]. A jamming component in a relay station for digital terrestrial broadcasting can be cancelled by adaptive digital signal processing [680].

5.2. ANC in Cable Links

If telephone communication for sparsely populated regions is transmitted via the power line network, employing a frequency division multiplex system, it is necessary to provide a high-impedance bridging to all but the RF signal destined for a respective subscriber; this can favorably be accomplished by a feedback cancellation technique as outlined in [681].

The adaptive cancellation of *transmission line echoes* was first examined in the context of long-range telephone communication when satellite links came into operation and electronic echoes severely degraded speech transmission (due to the long echo return time of almost 0.5 s, via geostationary satellites at 36 000 km height) [22, 33, 48], [682]–[724]. In order to reduce the controller complexity, it is suggested in [725] to use a sigma-delta converter instead of a conventional A/D converter. The stability of an echo canceler in the presence of strong noise can be improved by comparison of a long-time average with a short-time average of an input signal and stopping the filter update when the short-time average falls below the long-time average [726]. Further improvements of line echo cancelers by the same assignee are [727] evaluating non-linear and linear power estimates, [728], [729] including acoustic echo cancellation (see next Section) and [730] with a dual filter method. The adaptation of the echo canceling filter is performed when only a far-end speech signal is detected; according to [731], the adaptive filter performance can be improved by utilizing a near-end speech detector at the echo canceler output (the "E-side") rather than at the input (the "Y-side"). A fast voice/no-voice discriminator is disclosed in [732], based on a time-series histogram to provide faster onset of the echo canceler filter adaptation when voice is detected. In [733] an improvement of the convergence behavior is proposed by applying a low-level auxiliary noise signal which is uncorrelated with the speech signals, thereby speeding up the adaptation process of the filters. Hands-free voice communication with line echo canceler and speech recognition is disclosed in [734], comparing the "words" received by the near-end microphone with those from the far-end echo.

An acousto-optical delay line with active cancellation of acoustic echoes propagating along the optical fiber is disclosed in [735].

Substantial echo cancellation is also required for *digital data transmission* through telephone lines [736]–[740], in particular also for ISDN interfaces [741]. The echo cancellation technology applied to modems allows higher data transmission rates or reduced error rates [742]. Degradation of the echo cancellation by d.c. offset is avoided by a drift compensation circuit as described in [743]. A series of patents deals with modems for combined data/fax/voice communication, emulating a telephone and providing howling and echo cancellation [744]–[747].

5.3. Acoustic Echo Cancellation in Communication Links

While the above cited patents address the cancellation of electromagnetic field interference, some early patents on comparable acoustic problems can be found, too. A pair of patents [748, 749] suggest an arrangement of a microphone pair and a loudspeaker for suppressing or canceling acoustic feedback.

The problem of acoustic echo cancellation or dereverberation became important with hands-free telephoning to improve speech quality, and in teleconferencing etc. also to break the feedback loop (local microphone → remote loudspeaker → remote microphone → local loudspeaker → local microphone) which may cause howling instability. In teleconference or hands-free telephone systems, the reduction of speech distortion by multipath transmission in the transmitter room (i. e., dereverberation) is possible by receiving the signals with a multitude of spatially separated microphones, splitting up each signal in several contiguous frequency bands and subsequent processing, either utilizing the location- and frequency-dependent interference [750], or applying a cepstrum technique [751]. A two-microphone system and signal processing in the frequency domain for dereverberation is disclosed in [752]. Acoustic feedback in hands-free telephone communication can also be avoided by shifting the carrier frequency of the audio signal with the help of an auxiliary modulation [19] (see also Section 2, 2nd paragraph).

A start-up training method for an echo canceler in teleconference rooms is disclosed in [753], applying a test signal for adaptation, and then holding the filters constant during the conference. An echo canceler with permanent adaptation is disclosed in [754], however stopping adaptation during double talk to ensure stable performance. This is also the essential feature of [755] and [756], stopping the adaptation when near-end speech is detected. An improved algorithm guaranteeing stability of the adaptive filters in multichannel digital voice transmission for teleconferencing during double talk is disclosed in [757]. A "double echo canceler," providing adaptive reduction of both line echoes and acoustic echoes in hands-free telephones is presented in [758], including speech and double-talk detectors, near- and far-end power comparators, and variable gain control for both incoming and outgoing speech. An echo canceler for teleconference systems with stereophonic transmission is disclosed in [759, 760] with means to automatically switch between mono and stereo reproduction in order to save the perceived sound image from flickering around in case of double talk.

A method to speed up filter convergence in acoustic echo cancelers employing the LMS algorithm has been described in [163] (see Section 2). An echo suppressor for a hands-free digital radio telephone system employs a speech activity detector which controls a variable gain amplifier [761]. Similar systems for echo cancellation and howling prevention in hands-free telephones are disclosed in [762]–[773]. An acoustic echo canceler for sound field reproduction in rooms records first the room echoes and then superimposes pseudo-echoes to the sound signal which, after transmission from the loudspeaker, cancel the room echoes [774]. A more direct way to eliminate room resonances is outlined in [775], suggesting extra canceling loudspeakers located at the walls from which the primary sound is reflected.

An acoustic echo canceler for teleconference systems effective in both directions is disclosed in [776]. The continuation of this patent includes digital voice enhancement [777]. Feedback cancellation for a hands-free telephone set is achieved in [778] by a second microphone inside the telephone enclosure next to the loudspeaker, and subtracting its output signal from that of the voice microphone. A different method of acoustic echo cancellation for full duplex audio telecommunication is disclosed in [779], discriminating between single and double talk condition by a frequency domain procedure, thereby deciding when to adapt the filter coefficients. The calibration of an adaptive beamformer for acoustic echo cancellation in hands-free telephoning is addressed in [780]. A compact teleconference terminal is disclosed in [781, 782], providing a conventional video monitor with loudspeakers, plus an array of microphones and acoustic echo cancellation electronics.

A microphone/loudspeaker system facilitates speech transmission between front and rear passengers in a car [20]; to prevent howling, a frequency shift by typically 5 Hz is applied (see also Section 2, 2nd paragraph). Similar systems are disclosed in [783], providing a two-microphone/two-loudspeaker system with howling prevention by one or more notch filters tuned to the resonance(s) of the vehicle compartment, and in [21] where feedback instability avoidance by, again, a slight frequency shift is suggested also for speech-operated vehicle controls. A voice enhancement and hands-free telephone system with noise reduction filters and equalization for use in vehicles is disclosed in [784], comprising several microphones and loudspeakers to facilitate conversation between passengers and with telephone partners; a microphone steering switch allows the selection of a specific active microphone. A simplified version of this communication system is described in [785]. A voice enhancement system for passenger compartments in automobiles with a microphone array, adaptive beamforming and speech source tracking is outlined in [786], evaluating the coherence of the microphone signals, also with respect to more reliable recognition of speech commands for vehicle control. An adaptive speech enhancement system with ANC for voice communication among vehicle passengers is disclosed in [787], including a speech detector. Engine-related periodic noise in the communication signal of hands-free telephoning in vehicles can be canceled by a system disclosed in [788].

The speech quality in vehicles often suffers from a loss of low-frequency components; in [789] a method is disclosed for reconstructing them from mid-frequency components by evaluating the residuum from the difference frequencies of higher harmonics. To enhance privacy for persons during hands-free telephone calls from inside a vehicle and to prevent other passengers from unauthorized listening, it is suggested in [790] to play music masking the speech sound and to remove this masking sound from the microphone signal by adaptive noise canceling. A speech reinforcement system for a multi-passenger van is presented in [791], providing – instead of echo cancellation – a microphone array with adaptive beam steering to the momentary speaker and adaptive null steering to the loudspeakers, thereby avoiding acoustic feedback and howling. A similar system with automatic volume control is disclosed in [792].

An acoustic echo canceler for teleconferencing as proposed in [793] estimates the echo by a frequency domain adaptive filter and subtracts the estimate from the near-end microphone signal to provide an echo-reduced communication signal. The amount of computation necessary for the adaptive filter update is reduced by leaving the first filter coefficients constant, corresponding to the initial time delay in the echo path which is estimated from the impulse response [794]. Howling in teleconference systems can also be prevented by placing the microphone at the midpoint between two oppositely phased loudspeakers so that their signals cancel each other out at the microphone [795]. An adaptive noise canceler for full-duplex communication by speakerphones etc. is outlined in [200] (see also Section 2). Both line echo and acoustic echo cancellation is the subject of [796], disclosing means for canceling residual echoes which provide smooth transitions between the amount of cancellation present at near-end speech only and double talk.

Speech transmission from a talker in a noisy environment can be improved by simulating the "cocktail party effect," employing two spatially separated microphones and utilizing the cross-correlation properties of their output signals [797]. Speech transmission by hands-free telephones from noisy environments where the disturbance is impulsive in nature can be improved with a microphone array and a canceling network comprising delays, adders, subtracters and signal processors [798]. The patent [799] is related to the cancellation of repetitive noise superimposed to low-level speech signals as encountered in firemen's voice communication when they wear a breathing apparatus in hostile environment. A further early patent proposes suppression (but not cancellation) of acoustic echoes in a reverberant room by correlation enhancement of two spatially separated microphones [800].

Multichannel sound field reproduction with inverse filtering to provide dereverberation and echo cancellation in rooms is outlined in [801], the same technology being also applicable to remove multipath ghost images in electromagnetic wave propagation.

The creation of a synthetic spatial auditory environment for teleconferencing systems is outlined in [802], applying binaural sound pick-up.

The problem of *howling prevention* occurs also in conventional electroacoustic *sound reinforcement* or *public address systems* where the microphone should not pick up too much sound energy from the loudspeaker. Compared to early systems for howling prevention in two-way communication links by voice-operated gain control (blocking the non-transmitting microphone, e. g., [803]), the adaptive feedback cancellation brought a considerable improvement. Some of many patents in this field are [139, 209, 210, 208], [804]–[843]. A different approach for a digital voice enhancement system is presented in [844] where the microphone output signal is monitored, and when it becomes sinusoidal this is considered an indication of howling onset and the loop gain is reduced. Howling prevention in public address systems is also the subject of [845].

Some patents on the improvement of *speech and data transmission* have been reported in Section 2: [58, 61, 140, 168, 175, 194] . A noise suppression system for speech enhancement based on spectral information is outlined in [846], judging that rapidly varying spectral components belong to the speech signal while temporally constant spectral parts are supposed to be noise and may therefore be suppressed. Adaptive noise cancellation to be applied to telephoning from noisy environments is disclosed in [847], applying a microphone array mounted in the telephone set and enhancing the speech signal by summing up the appropriately delayed microphone output signals. A hands-free (speaker) telephone with adaptive cancellation of both electric and acoustic echoes is outlined in [848]. A telephone system providing both handset and hands-free mode uses a two-part echo canceler where a feedback loop presets the echo canceler in the handset mode so that after switching into the hands-free mode the canceler adapts faster [849]. A telephone handset with adaptive noise canceling is intended for use in noisy environments, having a second microphone at the outside of the handset to pick up external noise, an error microphone in front of the loudspeaker within the handset, and two adaptive filters, one reducing the ambient noise from the outgoing signal, and the other one to provide the talker with his own voice [850]. In order to provide hands-free telecommunication without headsets, a coat-like garment is proposed in [851] which is equipped with several loudspeakers and microphones; feedback cancellation is achieved by multiple adaptive filters employing the LMS algorithm. In [852] a two-channel system is disclosed where a fixed filter cancels the direct path echo, and an adaptive filter cancels the room echo. In a companion patent [853], a slowly converging adaptive echo canceler with a long FIR filter cancels the stationary echoes, and a faster converging canceler with shorter filter in series with an adjustable delay accounts for the time-varying components due to persons moving in the room, etc. A speakerphone system with both acoustic and electric line echo cancellation by digital control of loop gain and volume is described in [854], and with additional double-talk detection in [855]. A hands-free telephone set with dynamic gain control for optimum analog-to-digital conversion of the microphone signal is provided with corresponding gain control in the acoustic echo cancellation path [856]. In [857] a two- or three-channel system is described which removes room reverberation from a speech signal by inverse filtering where the filter tracks variations in the room impulse response. A robust multichannel acoustic echo canceler is described in [858]: modified FIR LMS filters are adapted with an optimized autocorrelation matrix whereby the adaptation regressor signals are sheltered from acoustic signal components. To speed up the filtering process in adaptive cancellation of acoustic echoes for hands-free telephone sets, a parallel filter bank with quadratic residue decomposition and a fast recursive normalized least squares algorithm is described in [859]. The problem of reliable system identification in adaptive filtering for echo cancelers and noise cancelers in case of a low signal-to-noise ratio and/or non-stationary signals is addressed in [860] where the adaptation algorithm utilizes long-term and short-term power estimates, step size setting and convolution to enhance performance stability. Robust adaptive control of microphone arrays for echo cancelers and speech enhancement in case of multiple speakers and background noise, e. g., for hands-free telephones or teleconferencing systems, is achieved in [861] by estimating the relative gains and time delays of the individual microphones. In digital subscriber lines (DSL) carrying both voice signals and data, the problem occurs of audible harmonic distortion when conventional telephones are connected to the communication line; a combined distortion and echo canceler is disclosed in [862]. Videoconferencing with enhanced spatial illusion by creating a virtual seating arrangement of the remote site is possible by multichannel digital signal processing [863]. A speech enhancement device using a spectral subtraction technique to improve the signal-to-noise ratio is presented in [864], including a voice activity detector and a smoothed Wiener filter. Speech enhancement by reduction of ambient noise is also facilitated by a voice activity detector employing an adaptive Wiener filter, as disclosed in [865].

A multipurpose acoustic signal processor is described in [866] which can either be used as a monaural dual speaker/microphone peripheral in telecommunication links with acoustic echo cancellation, or for wideband stereo sound field reproduction without echo cancellation. [867] employs adaptive beamforming, which is also the subject of [868] and [869] for speaker detection and sound field reproduction in teleconferencing. Speech transmission with improved noise reduction by microphone arrays is possible by combining the advantages and avoiding the shortcomings of two previously known techniques; the procedure is outlined in [870] where an adaptive Wiener filter is updated using auto- and cross-power spectra, combined with a speech detector to make SNR estimates independently of cross-power estimates. Telephone handsets or protective helmets with communication signal inputs and microphones picking up external noise provide considerable noise cancellation by applying difference amplifiers [871]. Adaptive beamforming can simultaneously focus to pick up sound from a desired direction, and null-steering of the directivity pattern to suppress disturbing noise sources [872, 873]. Improved adaptive beamforming for one-, two- and three-dimensional microphone arrays is described in [874]. The construction of a two-dimensional electret microphone array is disclosed in [875]. Speech transmission from a noisy environment such as a car is improved by a microphone array, a filter bank and an array of adaptive beamformers for each frequency subband, thereby suppressing noise [876].

The technology of *adaptive noise cancellation* (see Section 2, 3rd paragraph) has been applied to speech transmission, typically with one microphone near to the speaker recording both background noise and speech, the other one so far away (or shielded: [877]) that it essentially picks up the noise input only [46, 47, 49, 867, 186, 187, 188, 189], [878]–[895]. If both input signals have not only correlated noise but also correlated speech portions, then a crosstalk cancellation procedure is desirable prior to the adaptive noise canceling [896]. The problem of adaptive noise cancellation for hands-free telephoning from vehicles where the two microphones necessarily have correlated noise and speech inputs is solved in a different manner in [897]: a power monitoring circuit switches the adaptation process on during steady-state operation, assuming absence of voice signals, and suspends the coefficient update during speech intervals. Adaptive noise canceling in the case of multiple noise sources distributed over a region, e. g., for speech transmission from aircraft cockpits, is treated in [884] by providing a multitude of narrowband adaptive filters with few filter parameters in each channel. A multichannel adaptive noise canceling system, preferably for application in vehicle enclosures, is described in [894]. A speech recognition system with sort of an adaptive noise canceler is disclosed in [898] where both microphone signals are processed with time segmentation, and the best fitted reference segment is selected for noise or music elimination from the corrupted speech signal. Adaptive noise cancellation and crosstalk cancellation, applied to communication signals from noisy office rooms, can be improved (avoiding reverberant-like sound signals) by splitting the crosstalk filter in a fixed pre-filter and an adaptive filter section [899]. Adaptive speech recognition in a noisy environment (e. g., an automobile) is possible with hidden Markov models and the cepstrum technique [900]. Speech transmission from vehicles by hands-free telephones is improved by spatial tracking of the talker with the help of a microphone array and adaptive beamforming [901].

Systems for the improvement of *voice transmission* from emergency vehicles notching out the siren noise by adaptive comb filters have been mentioned in Section 2 [53, 144]. In [891] a voice enhancement system is outlined where the signal-to-noise ratio is improved by frequency-dependent gain control in the low-frequency subbands, employing a time-efficient recursive algorithm. Another voice enhancement system for telecommunication networks includes input power estimation to adjust gain control settings from a lookup table, bass band equalization, and voice band data detection to disable the voice enhancer [902]. Noise suppression for mobile phones can be achieved by a two- or three-microphone system providing a type of beamforming [903]. A similar device with adaptive noise canceling is disclosed in [904]. The speech quality of calls received by hand-held telephones depends considerably on the distance between the receiver and the ear, due to the varying acoustical impedance seen by the loudspeaker; the patent [905] provides a method of adaptive spectral equalization, controlled by the sound pressure measured with an additional sensor.

The patents [906] and [907] present enhanced-privacy telephone handsets with a built-in loudspeaker at the outside to cancel the radiation of talker's voice into the surroundings. The ANC technique can also be utilized to compensate for nonlinear loudspeaker distortion (see also Section 17 on transducers). Privacy enhancement in open-plan offices for hands-free telephoning etc. is provided by adaptively controlled loudspeakers creating an invisible sound shielding screen, according to [908].

A voice activity detector for use in telephone systems with voice recognition capability is disclosed in [909].

6. ANC FOR PERSONAL NOISE PROTECTION

A field where active noise canceling has found considerable technical application is *personal noise protection* (the German expression *persönlicher Schallschutz* is quite common). The systems comprise actively controlled earmuffs and earplugs, headsets with voice communication, and hearing aids.

6.1. Hearing Protectors and Earplugs with ANC

ANC for hearing protectors has first been proposed by Bykhovskii in 1949 [910], and many improvements towards technical products with electroacoustic cancellation have been documented later on [397, 867, 96, 179], [911]–[926]. An earcup assembly with purely mechanical cancellation of the transmitted noise is outlined in [927]. A frequency-selective ANC system for hearing protectors blocks only those frequency components which exceed a certain threshold [928], applying FFT and adaptive filtering. Protection of headsets etc. with feedback ANC systems against overload by intensive very low frequency noise is possible by a second external microphone the output of which is low-pass filtered and then subtracted from the error signal [929]. A feedback system with a perforated plate in front of the sensor microphone reduces the influence of individual impedance variations of the ear on the system performance [930]. An active micromechanical unit fitting into the ear canal and providing low-frequency noise cancellation is outlined in [931].

An active headset or ear defender with adaptive feedforward and delay control cancels tonal more than random noise [932]. Earmuffs providing speech transmission in noisy environment [933] include directional microphones, adaptive band-pass filters with gain control and speakers, so improving the signal-to-noise ratio.

6.2. Communication Headsets with ANC

A further development is the active noise canceling headset with communication input [914], e. g., for industrial workers, and in particular for aircraft pilots [402], [934]–[970] and (however without ANC) for ground crew members [971]. An advanced noise canceling system for both handset and headset telephone receivers is presented in [972] where besides a conventional feedback cancellation circuit an instability monitoring stage adjusts the feedback gain to stable values and preconditioning filters shape the incoming voice signal to near optimum spectral response. [973] claims simplified manipulation and improved connection with conventional audioelectronic devices, but without detailing the technical realization. A noise-canceling headset with adjustable broadband noise reduction is said to minimize the subjective pressure felt in the user's ears [974].

An open-backed headset with adaptive feedforward control utilizes the error microphone signals at the ears as outgoing speech signals [975]. The patent [976] employs active sound field control for audio music reproduction with headsets towards a specified desired performance at the listener's ear.

A leak detector for pipe systems with fluid flow comprises a flow noise sensing microphone and a monitoring headset with active cancellation of ambient noise [977].

A headset to be worn in high ambient noise (aircraft, military vehicles, helicopters) where the noise canceling actuator is a vibrator acting directly on the headset shell is disclosed in [978]. An improved design of a headset with feedback ANC is disclosed in [979], enlarging the internal volume of the earcup by perforation of the sealing, and including a passive resonance suppressor by a wire mesh screen covering the microphone and loudspeaker arrangement. An active noise canceling headset with adaptive feedforward control accounting for the sound field modification by reflections from the listener's head to the proximate ANC microphone is disclosed in [980, 981]. A headset for pilots with ANC and a classifying system deciding whether an external sound is noise or a message (e. g., the copilot's voice, or a warning signal) and therefore to be suppressed or transmitted, is disclosed in [982].

A voice transmission system for talkers in high ambient noise conditions (e. g., racing cars pilots) is outlined in [983]: the microphone is placed at the inner side of a tight sealing earplug deep in ear canal and receives the weak outbound voice sound caused by the reversed motion of the tympanic membrane when the earpiece wearer speaks. Residual external noise is received by a second microphone at the outside of the earplug and actively cancelled by feedforward control. Adaptive noise canceling and equalization are the subject of [984], intended for use in, e. g., call centers where the operators use headsets and are exposed to ambient noise.

In order to avoid "acoustical isolation" of persons wearing active or passive headsets, it is suggested in [985] to provide the headset with an outside microphone to pick up ambient signals which can be suppressed or enhanced manually, relative to an external audio or intercom input.

6.3. Hearing Aids with ANC

A number of patents can be found on hearing aids with ANC. In [986], three microphones are placed with different spacing, and either two components are summed to provide directional receivers for certain frequency bands, each being band-pass filtered, and then summed again to give a broadband directional receiver to compensate, e. g., for the lost ability of directional hearing of the hearing impaired (cocktail-party effect). A directional hearing aid with more than two microphones is disclosed in [987], either two microphones can be combined to provide a directional receiver for different frequency ranges. A hearing aid with howling prevention by adaptive noise canceling is disclosed in [988]. Further patents on this subject are [989]–[1013], some of them dealing with electronic compensation of acoustic feedback. A supply voltage regulator for hearing aids with feedback cancellation stabilizes their performance [1014]. Feedback cancellation in public address systems and hearing aids can be accomplished by a modulation technique and a phased-locked loop [209].

Programmable hearing aids with automatic adaptation of their transmission characteristics to the individual situation and changing environmental conditions are provided with fuzzy and neural network control [1015, 1016, 1017], and in [1018] combined with a tinnitus therapy by digitally creating an optimal masking sound. A hearing aid with a microphone array mounted on an eyeglass bow, and sophisticated signal processing for adaptive beamforming is disclosed in [1019] for adaptive minimization of reverberation in the output signal and optimization of the signal-to-noise ratio. The control efficiency of a hearing aid can be raised by performing automatic gain control at the input and at the output by the same amplifier [1020]. A digital hearing aid with variable directional microphone characteristic is disclosed in [1021], applying a sigma-delta converter and a delay unit for the resulting 1-bit signal. A hearing aid with at least two microphones and noise suppression by adaptive null steering of the directivity pattern is claimed in [1022].

A hearing aid with dynamic compression is provided with a gain control circuit to prevent internal acoustic feedback [1023]. A hearing aid with a microphone array worn as a necklace is presented in [1024]; the directivity pattern is adjusted by optimal filtering of the microphone signals, and the signal transmission to the earpieces is wireless. This is obviously an improvement of [1025], disclosing wireless transmission from the necklace to the earpiece, and including a "telecoil" for better understanding of telephone speech.

ANC in a telephone handset compatible with magnetically coupled high fidelity hearing aids provides true signal reproduction and room noise suppression [1026].

7. ANC FOR DOMESTIC APPLIANCES

A *refrigerator* with active cancellation of pump and compressor harmonics has been manufactured by the Japanese company Toshiba; several Japanese patents related to this development have been submitted [1027]–[1038]. Multichannel ANC of periodic refrigerator noise by adaptive feedforward control with synchronizing input is also disclosed in [1039]. Active reduction of compressor noise in coolers, combined with performance optimization, can be achieved by controlling a variable width diffuser and the position of pre-rotation vanes [1040]. A certain amount of noise and vibration reduction of refrigerators, air conditioners etc. is possible by avoiding fan and compressor speeds which excite appliance resonances; in [1041] a digital controller is described which avoids critical frequencies by comparison of the actual speeds with values taken from a data storage and according adjustment of the driving voltages.

Fan noise cancellation in general, and especially for *air conditioners* and *computers* is the subject of [1042]–[1059]. Fan noise and vibration caused by nonuniform air flow can be cancelled by moving the propeller hub back and forth in synchronism with the (repetitive or random) disturbance [1060]. ANC in particular for *kitchen exhausts* has been proposed by [1061]–[1065], and for *vacuum cleaners* by [1066, 1067].

An active feedback noise canceler for *impact printers* is proposed in [1068]. Noise of *copying machines*, generated by fans and the mechanical transport system, shall be cancelled by an active feedforward system as outlined in [1069].

Adaptive noise cancellation for a *video camera*, to remove motor noise etc. from the speech signal, is proposed in [1070, 1071] and [1072]. In [1073] is proposed the distribution of ANC signals to several domestic appliances from one central DSP via power line transmission by a modulation technique so that only the transducers, amplifiers and (de)modulators have to be installed in the individual appliance.

Elevator cable winch vibration which causes noise radiation into the machine room on the topmost floor of a building and from there down through the cable holes shall be canceled actively by a system disclosed in [1074], applying feedforward control with the vibration signal as input, a noise predictor circuit, a sound signal generator and loudspeakers to radiate the canceling sound.

A naive patent application [1075] claims to record typical annoying sounds and to replay them with opposite phase to cancel disturbances, ignoring the demand for precise parameter adjustment.

8. ANC FOR EXTERIOR NOISE

Technical applications of ANC to three-dimensional exterior noise problems are still quite rare, but a number of patents exist. A sound source localizer with a microphone array is disclosed in [1076], providing cancellation of repetitive noise which is necessary when the localizing system is mounted on a vehicle (as in military equipment). Two patents on algorithms for sound and vibration control in three-dimensional spaces have been cited in Section 2 [59, 76] . Reduction of vehicle exhaust noise by active systems mounted at the tail pipe has been discussed in Section 3.2. An adaptive feedforward system for controlling acoustic or electromagnetic noise with wireless error signal transmission is proposed in [1077]. To create a "zone of quiet," a multichannel feedforward ANC system with feedback cancellation is disclosed in [1078, 1079], but the particular algorithm problems of such systems are not addressed. Also a later patent [1080] claims to protect urban areas from traffic noise etc. by a loudspeaker array and multichannel feedforward control from a microphone array, but the necessary signal processing steps are addressed only superficially.

8.1. ANC for Propeller Aircraft and Helicopter Noise

Some patents are related to the reduction of propeller aircraft noise [1081]–[1086].

The fly-over impulsive noise of helicopters in descent flight is caused by blade–vortex interaction. This noise can be reduced by trailing edge flaps near the tip of the rotor blades which are actuated during rotation in relation to the rotor azimuth [1087, 1088, 1089]. Periodic air injection into and air suction out of the blade surface serves also to reduce vibration and noise created by blade-vortex interaction [1090]–[1094]. In [1095] and [1096] it is suggested to cancel the fly-over noise of a helicopter by an array of loudspeakers beneath the cockpit, being driven with a canceling signal in antiphase to, and with a directivity resembling that of the rotor blade noise.

8.2. ANC for Jet Aircraft, Gas Turbine and Fan Noise

Active noise canceling has been proposed for gas turbine or fan aircraft by fluid injection [1097, 1098] or other means [115, 503], [1099]–[1108]. A semiactive acoustic liner for absorption of fan or turbine noise in the housing of an aircraft engine is described in [1109]: the resonance frequency of a conventional liner is adjusted to changing engine speed by a feedback controller with a piezoelectric actuator in the back volume of the liner. A semi-active exhaust silencer for jet engine test sites is disclosed in [1110]: the flow duct is lined with cavity-backed porous absorbers, and to enhance the absorber efficiency at low frequencies, loudspeakers are placed in the cavities which are driven by a feedback controller so that the sound pressure at the microphones (just behind the porous layer) is minimized, thereby increasing the volume flow through the porous material and, hence, the sound absorption. A similar concept is presented in [1111]: a porous absorber is backed by an array of cells with oscillation plates in them which are driven so that almost zero impedance is maintained at the backside of the porous plate, thereby again providing enhanced absorption for low-frequency sound.

The exhaust noise of jet engines with gas turbines can be suppressed, according to [115], by an adaptive multichannel controller. Noise from airfoils in compressor or turbine sections of gas turbines etc. can be reduced by providing, near the leading edge, canceling sources such as vibrating pistons or resonance absorbers embedded in the airfoil, or by leading edge flaps [1112]. Fan tones from the bypass duct of jet aircraft can be cancelled by an array of impedance matching cavities in the nacelle wall, partly attenuating the noise propagating downstream, partly creating a reflected sound wave which propagates upstream in antiphase with the fan noise radiated from the air intake, thus silencing the jet engine noise particularly during aircraft take-off and landing [1113].

Tonal jet engine fly-over noise can be reduced by an adaptive feedforward controller acting upon a valve modulating a stream of pressure- and temperature-regulated air which is injected into the air outlet of the engine [1114]. Jet aircraft noise laterally radiated from the air intake mouth can be measured and cancelled by circumferential microphone and loudspeaker arrays with a multichannel feedforward controller [1115]; the theoretical background and cost functions for different control strategies are included in the patent.

8.3. ANC for Road Traffic Noise

The severe problem of road traffic noise is dominated by the tire/road surface rolling noise at speeds above about 50 km/h for cars and 60 km/h for trucks. A slight reduction is possible by applying sound absorbers to the wheel well, e. g., by passive resonance absorbers [1116], or by Helmholtz resonators which are adaptively tuned to the principal noise frequency band, depending on the vehicle speed [1117]. Loosely spaced cylindrical loudspeaker arrangements placed alongside highways are claimed to successfully cancel road noise in the neighborhood [1118] (but a test construction has been reported not to yield any reduction). Active control of noise radiation from road vehicle tires shall be possible by electromagnetic actuation of the steel reinforcement embedded in the tires [1119]. The active cancellation of noise radiated from rolling tires by piezoelectric loudspeakers mounted in the lower part of the wheel casing is proposed in [1120] where collocated feedback control with sensors integrated in the loudspeakers shall be applied. A short naive utility patent [1121] claims to cancel the road noise by emitting sound from a loudspeaker array beneath the car, driven from microphones near the tires, but without mentioning the problems of signal processing. Repetitive engine noise emanating from the air intake can be cancelled by a loudspeaker in the air inlet opening [611] (see also Section 4.6). An active silencer for the air intake duct is also disclosed in [1122], applying adaptive feedforward control and mounting the loudspeaker facing outwards from the duct so that its coil-and-magnet driving device is exposed to the air stream and thereby cooled.

8.4. Miscellaneous

A frequently discussed problem is the cancellation of *power transformer noise*, either by loudspeakers arranged around the site [1123], by force input to the oil in which the transformer is immersed [1124, 1125] or to the surrounding tank walls [36], or by sound insulating active panels enclosing the transformer [1126, 1127].

A *noise screen* for aircraft test sites etc. has been proposed, to be realized by a louver which generates destructively interfering plane waves [1128]. A similar idea of noise cancellation by interference has been disclosed in [1129] where a sound wave shall partially be guided through a medium of different sound velocity to obtain the antiphase condition. ANC for power plants with adaptive feedforward control has been proposed in [1130]. An actively supported *noise barrier* is disclosed in [1131]; the upper part of the wall is shaped as a double wall and ANC loudspeakers in the open top of the gap are operated in an adaptive feedforward control scheme to cancel the noise passing over the wall. Another actively supported noise barrier is disclosed in [1132]: the low frequency sound diffracted around the top edge of the wall is cancelled by a horizontal loudspeaker array which is mounted near the top edge and acts as a line source. A passive alternative for narrowband noise diffracted around the upper noise barrier is disclosed in [1133]: a ring of Helmholtz resonators around the top edge, approximating zero impedance and thereby reducing the diffracted sound field. Combined passive and active noise control at the upper edge of a noise barrier is disclosed in [1134], discussing a variety of arrangements.

The patent application [1135] claims to silence private pool and garden areas by loudspeaker arrays mounted on the roof of the adjacent house (one should not expect that this works in practice).

Adaptive feedforward ANC in situations where the error microphone cannot be placed in the region of desired control requires adaptation with an error signal obtained at a remote place. Control strategies for such problems are disclosed, for both single- and multi-channel systems, in [1136] and [1137], the latter one including a desired signal input.

Local ANC around a retail station, e. g., a fuel dispenser of a gas station, is suggested in [1138], applying feedback or feedforward control to create a "zone of quiet" for the customer.

9. SOUND RADIATION AND TRANSMISSION CONTROL, ASAC

Sound transmission through a fictitious partition can in principle be controlled by Huygens sources as described in the Introduction to this overview [11, 15, 1139]. Sound shielding by a grid of antisources has been proposed in [15] (see Section 1), and later on again with modern technology [1140, 1141]. Sound transmission through real walls at low frequencies can be actively reduced, either by an array of sound sources on or in the wall [16], [1142]–[1146], by intensity control inside the enclosure [1147], by double walls with active treatment [1126], [1148]–[1150], or by force input to the structure [502, 1151, 1152, 1100, 1153, 1127, 1154, 594, 1155]. The latter technology has been termed *Active Structural Acoustic Control* (ASAC). Sound and vibration transmission through windows can be controlled actively, according to [1156] and [1157], by laminating the window glass with a transparent piezofilm, e. g., poly vinylidene fluoride (PVDF) and transparent electrodes. Sound and vibration transmission through a wall can be blocked by connecting a perforated plate as electrostatic actuator parallel to the wall and applying an electric a.c. field between them which counteracts the primary wall vibration [12]. A similar system is disclosed in [1158], with an additional desired sound signal input to the actuator. Sound radiation from a vibrating panel can also be reduced by converting its radiating surface into a sandwich structure by coating it with a deformable (passive or active) layer on top of which a mass layer is mounted [1159], [1160]; the device acts as a passive distributed vibration absorber if the additional mass/spring system has a resonance close to a resonance of the primary panel, or as an active absorber if the deformable layer is, e. g., a PVDF layer with appropriate control.

Sound transmission from the outside into an aircraft cabin can be reduced by compact sound absorbers of the Olson type [8] placed in the trim panel, each absorber element comprising a loudspeaker, a microphone in front, and a feedback control circuit [1161]. Noise radiation into an aircraft fuselage from engine-excited trim panels can be reduced by adaptive tuned mass dampers [1162].

The problem of error estimation in the acoustic far-field of a sound radiating structure can, according to [1163], be solved by processing the signals of an array of accelerometers along the structure.

Sound radiation into the far-field from arbitrarily shaped closed shells under water can, according to [1164], not only be reduced by structural actuators, but also by a loudspeaker array inside the structure; a programmable controller predicts the far-field radiation pattern from near-field measurements around the shell and generates the control signals for the loudspeakers.

Repetitive noise radiated from a rotating or chopping machine is reduced by a combined feedback and tracking control system applying piezoelectric actuators [1165].

Sound transmitted through a wall can be cancelled by loudspeakers mounted along the wall, applying adaptive feedforward control with the reference microphone on the noisy side and the error microphone on the other side [1166]; the patent presents also actively treated double walls, and in addition to the filtered-x LMS algorithm also feedback control.

Sound radiation from vibrating panels in cars and aircraft, as well as structure-borne sound transmission through structural joints can be suppressed by piezo elements mounted between adjacent structural parts with appropriate feedback control [1167].

An adaptive feedforward ANC system canceling noise transmission through ventilation slots in windows or walls is disclosed in [1168].

10. OTHER ANC APPLICATIONS

Active cancellation of underwater *self-noise* picked up by a ship's sonar system can be achieved by initially recording the disturbance and, during operation of the sonar system, adding the frequency-synchronized, gain and phase controlled playback disturbance signal to the sonar signal in order to reduce the interference [1169]. An alternative with smart structures is shown up in [1170] (see Section 17), and a solution for the active control of nonstationary underwater or structure-borne sound in [78]. A system for self-noise cancellation of submarines by application of adaptive noise canceling is disclosed in [1171]. The self-noise picked up by a hydrophone array mounted along the ship hull can also be cancelled by picking up the hull vibration with accelerometers, resolving the hull vibration into its dominant modes and deducting the hull-induced contributions from the hydrophone signals [1172]. A similar device is disclosed in [1173]. In seismic exploration the problem occurs that a mobile (usually truck-mounted) vibrator not only excites the earth surface but also radiates air-borne sound which can be picked up by the geophones and mask the low-amplitude wanted signals; in [1174] a multi-loudspeaker method is disclosed to cancel actively the sound emitted from the vibrator.

Reduction of audible noise from a *gas turbine* engine is proposed, by modulation with an ultrasonic (siren) tone so that the noise spectrum is shifted into the ultrasonic range [1175]. A military application of ANC is proposed in [1176] for acoustic target seekers where the repetitive self-noise of a weapon is cancelled by a tracking filter with phase-locked loop.

Also *medical applications* are the subject of some patents. Adaptive noise cancellation (see [25]) has been applied to the improvement of electrocardiograms (ECG) in the operating room [1177] by canceling the interference caused by electrosurgical instruments. [1178] attempts to improve the signal-to-noise ratio of weak cardiac sounds, where the masking lung sound is detected separately and subtracted from the signal provided by the cardiac sensor (again an application of the adaptive noise canceling technique). A stethoscope for use in a noisy environment has two transducers, one sensing the body sound and the other one the environmental noise. The sensors are mechanically isolated from each other so that adaptive noise canceling can be used to improve the signal-to-nosie ratio [1179]. Stethoscopes with active cancellation of background noise are also described in [1180, 1181, 1182, 1183], in [1180] with fluidic pressure sensors and amplifiers. In [1184] and [1185] is described how vibrational noise produced by a medical or dental instrument in the head of a patient can be cancelled by an adaptively controlled signal applied to headphones or bone vibrators. Otoacoustic emission as a diagnostic tool of hearing impairment is suggested in [1186, 1187], employing adaptive noise canceling to enhance the weak signal. Blood flow measurements with the ultrasonic Doppler effect can be improved by adaptive noise-reduction low-pass filters [1188]. An ANC system to cancel the drilling noise to which dentist's patients are exposed is disclosed in [1189].

Several patents are concerned with ANC for *magnetic resonance imaging* (MRI) tubes where the patients suffer from loud noise pulses which are produced in synchronism with the magnetic pulses. Since ferroelectric materials must not be installed in the tube and even electric conductors can lead to image distortion, special technical solutions are required. In [1190], [399] and [1191] is suggested, among others, local ANC for the patient's ears in an MRI tube by a loudspeaker outside the tube and soft plastic tubes guiding the canceling sound to the ears; practical experience with a commercial product showed, however, very limited success, in particular with modern rapidly changing gradient pulse shapes. In [1192] it is proposed to mount actively tuned resonator plates with piezoceramic actuators to the inner surface of the MRI tube, and in [1193] to the gradient coils. The reference signals for the ANC systems can be derived from the gradient signal generators. A feedback ANC system with a headset including piezoelectric microphones and loudspeakers is outlined in [1194], the loudspeaker membrane being split into a series of narrow parallel strips to avoid eddy currents in the radio frequency (RF) field; in order to minimize the MRI signal distortion by the electric leads inside the tube, all leads are grounded (to a virtual earth, if necessary) for the RF frequency, by series resonance circuits arranged at a distance of a quarter wavelength from the headset, thus presenting to the currents at the RF field frequency a high impedance in the headset position.

Speech enhancement systems for communication with an MRI patient are disclosed in [1195] and [1196] where the SNR is improved by frequency band division and correlated averaging of two microphone signals, or by adaptive noise canceling [1197]. Electrodynamic ANC loudspeakers for application in MRI tubes are disclosed in [1198] and [1199], the magnets being omitted, instead using the inhomogeneous magnetic field within the tube. A noise canceler for speech transmission from the MRI patient to the outside operator applies a notch filter tuned to the central frequency of the gradient field pulses [1200]. Another solution of the MRI noise problem is presented in [1201]: the gradient coils are embedded in sound absorbing material, together with non-magnetic sound transducers to cancel the noise at the patient's ears. A series of Hitachi patents claims to reduce vibration and noise in an MRI tube by actively exciting the cylindrical gradient coil support with piezoelectric actuators to counteract the electromagnetic "wire forces" , [1202]–[1205].

Sleep apnea can be detected by a microphone placed near the sleeper's nose and mouth, applying adaptive cancellation of uncorrelated ambient noise, followed by a sound signal classifier with a filter bank [1206].

An application of acoustic echo cancellation has 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 [1207, 1208]. Similarly, the ANC technique can be applied to cancel the reflection of the ultrasonic echo from the receiver by an (analog) feedback control circuit [1209]. An ultrasonic transducer is described in [1210] with a lens containing an electrorheological fluid so that the focal length can be adjusted by applying an electric voltage to the lens.

A *musical wind instrument* with the variable tube resonances being replaced by electronic feedback control is described in [1211, 1212]; a non-reflective tube termination is realized by active impedance control.

Active control of repetitive *gear mesh noise* of electromotors is provided by adaptive tracking control of the driving torque by modulating the d.c. motor current [1213].

The cancellation of the hum produced by *electroluminescent (EL) devices* is the subject of [1214]; although the noise level is low, it can be disturbing when the EL device illuminates a liquid crystal display of, e. g., a mobile phone which is held very close to the ear.

11. ACTIVE FLOW CONTROL

An ionized gas stream in a combustion chamber (e. g., in a rocket) tends to cause unstable resonance oscillations which can be suppressed by an appropriately controlled electric d.c. current through the ionized gas, employing a feedback controller with a photoelectric cell as oscillation sensor [1215, 1216]. Gas turbine stall can be influenced towards a surge condition by modulating the fuel flow into the combustor plenum by feedback control, with the gas pressure in the plenum as input [1217]. A modal approach to active control of combustion instabilities is presented in [1218, 1219], again by modulating the fluid flow into the combustor, applying a magnetostrictive actuator. Self-excited combustion instabilities of a gas turbine can be controlled by a modulation procedure as outlined in [1220].

According to [1221], gas turbine combustion oscillations can be controlled by a combined passive and active controller, in particular by modulating the fuel flow. Flow instabilities, such as turbulence, can emerge from initially small boundary layer fluctuations and therefore, to a certain extent, be controlled by sound. Patents are related to the active acoustic control of combustion instabilities [1222]–[1228], and to drag reduction by acoustically controlling the Tollmien-Schlichting waves in the boundary layer [1229, 1230, 1231]. The noise produced by the centrifugal compressor of a chiller having a condenser, an evaporator and a variable width diffuser section can be reduced by adjusting the gap width in relation to the operational parameters (capacity and temperature difference) of the compressor [1040]. The control of gas or liquid flow pulsations is also the subject of [1232]–[1237]. In [1238] is presented a micro-electromechanical system to be mounted on fan blades, comprising a turbulence sensor, an integrated circuit, and an actuator by which turbulence noise can either be reduced, or – in case of heat exchangers – amplified in order to improve heat transfer. An acoustic sensor in fluid flow is disclosed in [1239], providing a microphone or other sensor placed at a proper position on the surface of a nose cone where flow noise is low. The microphone of an HVAC (heating, ventilation, air conditioning) ANC system can be protected against heavy turbulence by placing it in a cavity flanged to the outside of the flow duct and lining the duct with porous material, and preferably also subdividing the cavity by the same porous material to suppress internal flow recirculation in the cavity [1240]. The pulsating flow of refrigerant in a vehicle air conditioner creates impulsive noise which can be damped by an expansion chamber and a controlled valve at the inlet or outlet [1241]. Thermoacoustic vibrations in gas turbine combustion chambers can be minimized also by modulated fuel injection into the premixing burner [1242].

As mentioned in Section 8.1, blade-vortex interaction causing impulsive noise of helicopters can be reduced by controlling flaps at the trailing edges, and tip vortices of helicopter blades, aircraft foils, or marine propellers by repetitive fluid injection into the high-pressure side of the lifting body , [1087]–[1091], , [1092]–[1094], [1243]. Oscillating air jet flow can delay the boundary layer separation from, e. g., helicopter blades and thereby improve the flight performance [1244].

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 [1245]. Cavity resonances excited by air flow over a cavity opening (e. g., a car with open sunroof) can actively be suppressed by generating a cross-flow at the inside of the opening, either by oscillating flaps at the leading edge of the opening, or by a feedback-controlled inside loudspeaker near the leading edge, or by periodic air blowing and suction at the opening, or by loudspeakers somewhere in the vehicle cabin, or by vibrating cabin walls, e. g., the roof [1246].

Flow-induced pressure oscillations in a duct create sound waves travelling downstream and upstream; an ANC system with two microphones, one loudspeaker and an adaptive IIR filter can cancel the upstream sound wave [1247].

12. AVC FOR BEAMS, PLATES AND STRUCTURES

Active damping of aircraft skin vibration has been proposed in 1942 [1248], providing multichannel feedback control with displacement sensors and electromagnetic actuators, mainly in order to prevent fatigue damage. 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 electric resistor [1249]. Resonance vibrations of the control rod in Diesel engine fuel injection pumps can be damped by a magnetic or electromagnetic actuator directly acting on the rod [1250].

In order to avoid vibration transmission along a (one-dimensional) structure, a *beam*, the application of both translational and torsional forces to the structure is proposed, thereby confining vibrations to certain regions of the structure and to preserve low vibration levels in sensitive regions

[1251], in some patents also including vibration damping by both passive and active means [1252]–[1255]. Damping control for bending vibrations of a rod-like structure is also possible by filling an internal cylindrical space with an electrorheological fluid and arranging a stack of electrode disks inside so that the bending stiffness and the loss factor can be controlled electrically [1256].

AVC in beams and plates is related to wave mode control in structures [1257]–[1260], and to canceling vibrations by combination with shape memory alloy wires [1261, 1262] or other actuators [511], [1263]–[1273]. In order to cancel or attenuate chassis vibrations of cars, a feedback control strategy is proposed in [1274], employing piezoelectric sensors and actuators to detect chassis vibrations and to generate canceling forces in diagonal stiffeners which are fixed to the car bottom, so that both longitudinal and torsional vibrations are damped. Torsional body vibration of a car with convertible roof can be reduced by a single active mass damper, suspended between a front suspension assembly and a bumper [1275].

Combined active and passive vibration damping of *plates*, including sound radiation suppression, is possible by a constrained layer damping treatment; [1276] shows several possible realizations and experimental results, obtained with piezoelectric transducers and feedback control of the first plate bending mode. Vibration control of printed electronic circuit boards is suggested in [1277], the piezoelectric or electrostrictive actuator being mounted on straps of any material so that it bridges over the electronic parts or wiring.

Stabilization of platforms on ships, carrying antennae for satellite radio links, including position and pointing control by multichannel feedback is outlined in [1278].

An early NASA patent [1279] provides an active mass damper to cancel *structural vibration*. An active mass damper with collocated feedback control, in particular for submarine hulls, is disclosed in [1280]. A similar system for particular application to helicopter cabins is presented in [1281], providing a servo-controlled vibrating mass with hydraulic or electrodynamic actuation. Active mass dampers, flexibly mounted to an aircraft or helicopter fuselage, are described in [1282], with many embodiments of actuation and spring design, and also devices for counterbalancing the moments of the dynamic mass absorbers. A similar system is disclosed in [1283]. A fluid-filled dynamic absorber with two activated masses, acting as a two-frequency absorber, is described in [1284], also outlining various embodiments. An active mass damper as resonance absorber with enlarged bandwidth of operation by feedback control is also disclosed in [1285]. Two-axial active mass dampers for application to repetitive vibrations of an aircraft fuselage or a vehicle cabin are disclosed in [1286, 1287]; the two vibration absorbers are mounted on a flexible beam which is attached to the vibrating structure.

A multichannel AVC system for canceling repetitive vibrations in aircraft etc. is disclosed in [1288], employing combined feedforward and feedback control with phase-locked loops for each frequency component. Wing flutter of aircraft carrying external loads under the wings can be suppressed by a semi-active suspension of the load [1289].

Swinging vibration of a helicopter fuselage suspended from the gear box can be damped by an actuator with a series spring which connects the gear box with the fuselage [1290]. A magnetically levitated reaction-mass actuator is proposed as a structural damping member in [1291]. A pneumatically controlled active mass damper for automobiles is disclosed in [1292].

Precision positioning and pointing control of structural members of any kind is the subject of [1293] and [1294], applicable to robotics, manipulators etc., including active vibration canceling with feedforward or feedback algorithms, piezoelectric and/or servo-controlled hydraulics. Damping and stiffness in mechanical junctions can be controlled by active dry friction dampers where the pressing force is adjusted by piezoelectric actuators, with feedforward or feedback control, typically by a nonlinear algorithm, e.g., a neural network [1295].

Stability problems in multi-degree-of-freedom systems by modal interaction can be solved by modal decoupling with the help of sum and difference steps in a multi-channel controller [1296].

Tracking control of structural vibrations is possible by decomposing an original signal of arbitrary frequency content into its band-pass filtered subsignals and canceling each of these narrowband signals with the help of a bank of phase-locked loops to generate the compensation signals [1297].

Vibrations of frequency-varying structures (spacecraft, snowboards, precision optical instruments etc.) can be damped by an adaptive shunt system [1298].

13. AVC FOR BUILDINGS

Bending vibrations of rod-like structural elements of buildings can be damped by actuating a seismic mass in a feedback control loop [1299]. Protection of buildings against earthquake and wind induced sway has been studied for years, often by applying dynamic absorbers, or so-called *tuned mass dampers* as resonance absorbers: a seismic mass is elastically connected to the top of the building so that the natural frequencies of building and mass damper are equal [1300]. Actively driving the mass in antiphase to the building vibration improves the vibrational energy absorption of the building [1301]–[1308]. A semi-active hydraulic vibration damping servomechanism for suppressing structural vibrations of buildings and bridges is described in [1309]; both ends of the assembly are pivotally attached to structural members, and the device can be operated to dissipate as well as store energy (in the latter case some air entrained in the hydraulic fluid is beneficial).

Earthquake and wind force damage prevention by a three-axial adaptive feedforward control system with a hydraulically operated reaction mass actuator and a sensor array to measure the primary excitation is described in [1310]. A simpler system is outlined in [1311]: high pressure hydraulic dampers on top of the building are connected to the roof frame by steel cables and driven by a servomechanism to absorb the swaying energy of the building. A simpler device for earthquake protection of buildings is disclosed in [1312]: an active truss element with kind of a hydraulic shock damper where a computer-controlled valve connects two chambers above and below the working piston and allows length adjustment of the truss element. An active floor impact noise suppressor is outlined in [1313], detecting the noise in the gap between upper floor and lower ceiling, and radiating the canceling sound from loudspeakers under the ceiling.

14. AVC FOR ROTATING MACHINERY

Rotating machines often exhibit vibrations due to unbalance, self excitation, etc. The dangerous resonance peaks during run up and run down can be avoided by temporary shifting the rotor resonance frequency with the help of feedback-controlled fluid film bearings, providing stiffness control and damping control [1314]. In turbomachines, the operating range can be extended by active cancellation of unsteady motion phenomena such as rotor blade flutter, rotating stall, or acoustic resonance [1315]. Unbalance control of a turbojet engine is disclosed in [1316], providing an unbalance measuring device and a double mass actuator mounted on the engine axis, with manually adjustable angular position and amplitude.

Torque control of electromotors by current modulation has been proposed in [1317, 1318, 1213], electromagnetic adaptive feedback control of axial vibrations by a reaction mass actuator in [1319], and AVC of, e. g., water-cooled pumps by driving a magnetically levitated mass in [1320].

Vibrations and structure-borne sound in rotating shafts of propellers, pumps, compressors etc. can be canceled by a variable reluctance actuator [1321].

Machine tool vibration (e. g., of a boring bar) can be controlled by an actuated mass in a sleeve holding the tool [1322]. Broadband damping for a boring bar machine tool is described in [1323] where the damping is provided by a purely resistive shunt of a piezoelectric (PZT) actuator; the inherent actuator capacitance is compensated for by a feedback controlled negative-capacitance shunt. A similar device is disclosed in [1324], applicable to the power drive train vibrations in vehicles; piezo sensors are attached around the bearing assembly, and the electrical current produced thereby is dissipated in shunt resistors. The damping characteristic can be adjusted by controlling the resistance and the piezo stiffness in response to a vibration sensor. Mechanical vibrations of a printing press can be reduced in a feedback loop by modulating the electrical input to the driving motors or by actuating an eddy current brake, thereby also improving the printing quality [1325]. Machine tool vibrations, e. g., of a milling machine, can be damped magnetically by attaching a magnetostrictive element to the vibrating machine, generating a magnetic field in response to the vibration, and a second magnetostrictive element in the vicinity to dissipate the magnetic field energy, so damping the vibration [1326].

A passive alternative of resonance suppression in rotating machinery is disclosed in [1327], employing a thixotropic fluid. An active mass–spring type resonance absorber is described in [1328] for damping, e. g., rotor-induced vibrations of a helicopter cabin. A hydraulic actuator is controlled to match the exciting force, and to adjust the absorber damping to its optimal value. Axial thrust vibrations in turbomachine shafts can be damped by a fluidic (gas flow) controller in a feedback loop, which also allows for failure accommodation of magnetic bearings [1329].

For rotating machinery in special environments, e. g., ultrahigh vacuum where conventional bearings cannot be applied because of lubricant evaporation, *magnetic bearings* without lubricant are preferred, but their inherent instability requires feedback position control which can be designed to simultaneously reduce vibrations [1330]. Also radial shaft or cylinder vibrations can be controlled by magnetic bearings [1331]–[1337] or, in particular for cylindrical shell rollers in textile machinery, by electromagnetic actuators placed pairwise orthogonally at the inside [1338]. An auto-balancing adaptive feedback controller for magnetic bearings is described in [1339]. A feedback control system for magnetic bearings with search coils as velocity sensors is described in [1340].

Multichannel systems can be applied to the adaptive modal control of vibrating machines with magnetic bearings [1341], and to tracking control for variable speed of rotation [1342, 1343]. A feedback position control system for magnetic bearings with magnetic flux sensors is described in [1344]. A multiple magnetic bearing for machine tool spindles with digital feedback control is outlined in [1345].

Repetitive vibrations in *vehicles* are typically induced by internal combustion engines with their inherent unbalance of the crankshaft at twice the rotational frequency (the "second engine order"). They can be reduced by attaching counter-oscillating masses [1346], or by an electromotor with unbalance (serving as a torque generator) where the frequency and phase are adjusted according to sensor signals taken at various places in the car and parameter values taken from a lookup table [1347]. Low-frequency vibrations in vehicles can be damped by a dynamic absorber formed by the battery as mass, a pivoting lever, and an elastic bearing at the other end; the mass position and the spring constant are automatically adjusted in a feedback loop to tune the absorber to the dominant vibration frequency [1348]. In some upper-class cars, the crankshaft unbalance is cancelled by a counter-rotating dynamic balancing second shaft, driven in synchronism by toothed belt transmission [1349]. A hybrid internal combustion/electric vehicle is disclosed in [1350], [1351] where the alternator rotates in opposite direction to that of the crankshaft and is controlled so that a zero net torque results, to minimize the vibration and noise level in the vehicle. A generator for an internal combustion engine with almost no roll torque is disclosed in [1352], the balancing being achieved by counter rotation of rotor and stator. Engine-induced vehicle vibrations can be cancelled in a straight forward way by two feedback controlled inertial mass shakers [1353]. Resonant torsional vibrations of a pulse-driven torque-transmitting shaft (as, again, in a vehicle with internal combustion engine) can also be damped by imparting periodic torsional impulses in the opposite direction to the twisting motion, e. g., by an eddy current brake acting upon a flywheel attached to the shaft, or with a magnetorheological fluid [1354, 1355]. In [1356] a device is disclosed for controlling vehicle engine vibrations by an active bearing of the rotating shaft, applying piezo elements between the shaft bearing and its mount and exciting them radially so that noise transfer into the passenger compartment is reduced.

Vehicle vibrations caused by rotational irregularities of the internal combustion engine ("roughness") can be cancelled by exerting a compensating torque with the help of the appropriately controlled alternator [1357]. Engine-induced structural repetitive vibrations can also be damped by attaching adaptively tuned dynamic absorbers which are realized as stiffness-controlled resonators [1358]. A knocking detector with variable time window is disclosed in [1359], promising an optimized decision procedure as a basis for ignition timing correction. Similar applications are [1360] and [1361]. In [1362] a multiple cylinder internal combustion engine is disclosed with enhanced fuel economy by deactivating some cylinders when less power is required; the pitch, yaw, and roll torques thereby induced are cancelled by a counter-rotating mass.

Wheel vibrations of a rolling vehicle can, according to [1363], be attenuated by an inertial mass ring around the wheel shaft, both being connected by elastic struts (which provide the static distance) and electromagnetic actuators, driven by a feedforward control device to reduce horizontal and vertical wheel vibrations.

Excessive resonance vibrations of bridges excited by traversing trucks can be avoided by active control of the truck's suspension stiffness and damping [1364], or alternatively by a control system that directly acts upon the bridge.

Periodic torsional and bending vibrations of the shaft of a rotating machine (e.g., again the crankshaft of an internal combustion engine, or the drive shaft of a multibladed grinding machine) can be absorbed by a mechanism similar to a centrifugal pendulum, but instead of a mass pivoting about a support, a mass freely rolling inside an appropriately shaped cavity is provided [1365].

Contact vibrations of rollers in a paper mill or printing press, caused by unbalance or deviations from circularity, can be reduced by adaptive feedback control of the force acting between the bearings of adjacent rollers, thereby preventing fatigue damage [1366].

15. ACTIVE VIBRATION ISOLATION

Active vibration isolation is the subject of a great number of patents. Many of them are related to active engine mounts and suspensions for vehicles, helicopters etc., with various actuation principles (electromagnetic, electrodynamic, piezoelectric, magnetostrictive, electrohydraulic, electropneumatic, hydropneumatic – sometimes with electrorheological or magnetorheological fluids –, linear motors), usually designed as hybrid systems with a passive load-carrying spring in parallel [9, 87, 92, 93, 356, 154], [1367]–[1490]. A method for three-axial acceleration control of a vehicle suspension using only a single obliquely oriented accelerometer and additional vehicle operation signals is disclosed in [1491]. Adaptively tuned vibration absorbers as part of aircraft engine mounts provide vibration isolation from the fuselage and thereby reduce vibration induced noise in the passenger cabin [1492]. In [1493] the passive and the active part are connected in series, and the construction is such that forces are transmitted only in lengthwise direction.

An aperiodic spring suspension is disclosed in [1494]: the mass load to be supported is connected to the base by a conventional spring with a "magnetic spring" in parallel, consisting of an electromagnet with an armature fixed to the mass load, and a feedback controller powering the electromagnet so that it exhibits a negative stiffness which compensates for the positive stiffness of the mechanical spring, thereby realizing a mass/spring system with essentially zero resonance frequency; thus a broadband vibration isolation is obtained.

A series of patents is concerned with extended application of hydraulics to various machinery. In [1495] a car is proposed in which the internal combustion engine drives a compressor only, the wheels being powered by a fluid motor providing a smoother ride, with additional hydraulic active vibration isolation. [1496] extends the same principle to helicopters, engine mounts, HVAC and buildings, improving the hydraulic vibration isolation by combination with air cushions. [1497] suggests two fluid accumulators, a high-pressure vessel for the wheel drive, and a low-pressure vessel for the auxiliary units of a vehicle; this two-circuit hydraulic system is extended to other applications in [1498]. To further improve the ride comfort of vehicles, the hydraulic vibration isolation can be combined with preview control, employing a road surface sensor mounted in front of the car [1499], or a pneumatic shock absorber [1500], possibly including an air cushion [1501].

In two-engine turbofan or turboprop aircraft, the problem of isolating the fuselage from sinusoidal engine vibrations with two closely spaced frequencies occurs, which often causes instability of an active system. In [1502] a solution is presented by appropriate positioning of active engine mounts.

A combined passive and active vehicle engine vibration isolation for trucks and tractors is presented in [1503]–[1505] where the static load is carried by a pneumatic system, while a hydraulic system provides the dynamic low-frequency isolation (high-frequency vibration is damped passively by elastomeric material). An active pneumatic mount is disclosed in [1506] where a pressurized bellows contains a loudspeaker enclosure by which, through a feedforward controller, the residual vibration transmission is reduced. An adaptive feedforward AVC vehicle engine mount cancels sinusoidal vibrations utilizing the filtered-x LMS algorithm, the error path identification being performed by a genetic algorithm [1507]. An active electrohydraulic engine mount for isolating the car body from harmonic engine vibrations employs the filtered-x LMS adaptive algorithm and a divergence monitoring and avoiding stage [1508].

An energy saving approach to vibration isolation for vehicle bodies, seats, or engines is outlined in [1509]: during one half-cycle of the vibration, energy is reversibly extracted from the structure, and returned in the other half-cycle, so avoiding external energy supply for driving an actuator.

Human comfort enhancement in any transportation vehicle is the purpose of [1510] where a combined passive and active isolation system is described to reduce both sway and heave motions of the passenger compartment. In [1511] a shock absorber for truck cab isolation from the chassis is developed which can switch between low and high damping, depending on the vertical chassis acceleration. The isolation of the passenger compartment from engine-induced vibrations is also the subject of [1512] where active engine mounts are operated by an adaptive feedback controller.

A *shock absorber* which isolates machinery vibration from, e. g., a submarine hull (in order to reduce low frequency sound radiation) is presented in [1396]; an elastomeric spring carrying the static load is supported by combined hydraulic and pneumatic controllers to compensate for dynamic force and torque transmission. Several patents describe active shock absorbers for various applications, including vibration isolation tables for vibration sensitive equipment [1513]–[1528]. A vibration isolating machine mount with fluidic controller is described in [1529, 1530]. Payload isolation from spacecraft support vibrations can be achieved by "S"-shaped brackets with piezoelectric bending actuators mounted to the vertical and horizontal connecting portions of the "S," driven from collocated accelerometers by H_∞ controllers [1531]. An active shock absorber with magnetorheological fluid is applied to reduce the vibrations of a washing machine which are excited by washload unbalance [1532].

Active removal of ground vibration disturbance from the digital signal of a weighing apparatus is disclosed in [1533], and active vibration isolation of a scanning (force) microscope from the support table by a feedforward control system in [1534].

To reduce vibrations of the litter support in ambulance vehicles, an active feedback-controlled system has been developed [1535] which maintains the good high-frequency isolation of a pneumatic spring with low damping, but avoids the resonance peak by stiffening the pneumatic spring at frequencies below twice the resonance frequency.

Active vibration isolation of a helicopter cabin from the gearbox and resonance suppression is possible by torsional bars and oscillating masses, serving as tuned mass dampers [1536, 1537].

Magnetic levitation as an active vibration isolation method is presented in [1538] for vibration-sensitive equipment (semiconductor fabrication, electron microscopes, etc.), controlling the displacement of a table relative to the floor and canceling vibration as monitored by an accelerometer mounted on the table and applying either PI or H_∞ control rules. A vibration-isolated table particularly for photolithography is described in [1539], providing a pneumatic control system for high-frequency and an electrodynamic system for low-frequency external disturbances, both controllers realized as combined feedforward/feedback systems. A two-stage vibration isolation system for use in micro-gravity experiments in spacecraft is disclosed in [1540], employing magnetic levitation and actively controlled magnetic force actuators that maintain alignment in all six degrees of freedom.

16. VARIOUS AVC APPLICATIONS

Automatic *roll stabilization* of ships is achieved by pumping water between tanks located on the two sides of the ship, in a feedback system with on–off control [1541], or with a more involved PID controller [1542]. Active roll stabilization of cornering vehicles by hydraulic control is disclosed in [1543]. The problem of detrimental modulation of an airborne radar oscillator by aircraft frame vibrations can be solved by an electronic master–slave system and a phase-locked loop [1544]. An active suspension for railroad vehicles providing tilt compensation in curves and high-frequency vibration cancellation accounting for rail irregularities is disclosed in [1545].

Power line noise in *seismic exploration* signals can be cancelled by properly adjusting amplitude and phase of a control signal which is derived from the power supply [1546]. Also in seismic exploration, the multipath propagation of vibrations caused by a test impact typically corrupts the geophone signals; in [1547] adaptive noise canceling and crosscorrelation are applied to compensate for interference resulting from near-surface waves. Another problem encountered in sea-borne seismic exploration occurs with so-called streamer cables, towed arrays of hydrophones, where the self-noise due to ship vibrations and sea motion can be cancelled by subtracting, from the hydrophone signals, stress signals recorded with piezoelectric stress sensors in the cable jacket [1548]. A further related problem is the impulsive noise cancellation in electromagnetic telemetry signals from borehole exploration, by filtering the signals in the frequency domain to remove the broadband noise floor, followed by an adaptive noise canceling stage to remove residual noise [1549]. Tool borne vibration can disturb acoustic exploration in fluid-filled boreholes; a method for active cancellation of the boring bar vibrations is disclosed in [1550], applying adaptive feedback or feedforward control.

An early patent on vibration and noise control of flying *helicopters* is disclosed in [1551], proposing a thrust ring around the (vertical) tail rotor which influences its tip vortices so that the tail rotor thrust is enhanced and the vibration and noise level is reduced. Modal control of helicopter blades is possible by individual blade pitch feedback control [1552]–[1568]. Torque control of helicopter blades by precession of gyros mounted to the blades is proposed in [1569]. Cyclic pitch control of a helicopter improves its flight performance and stability, and reduces vibration [1570, 1571]. Higher harmonic control of X-wing aircraft rotor blades is the subject of [1572], and as part of a flight control system in [1573]. An actuator for higher harmonic control with low power consumption is disclosed in [1574]: a slotted rotating cylinder mounted at the outboard section of each blade and causing an air stream which acts as a periodic lift force analogous to that of an oscillating trailing edge control surface. A helicopter multichannel AVC system can be combined with a "health monitoring system" triggering an alarm if the control parameters exceed predetermined values [1575]. A similar system is described in [1576] which provides in-flight structural testing by using one of the AVC actuators to shake the structure and to measure the structural response. Vibration damping of a helicopter cockpit by servo-controlled resonance absorbers of the mass/spring type is disclosed in [1281], and by a tuned mass damper in [1577]. A dangerous stall condition of the main rotor blades of a helicopter usually causes increased fuselage vibration. Higher harmonic (blade pitch) control (HHC) can damp the fuselage vibration to an extent that the pilot does not realize the stall condition in time; it is therefore suggested in [1578] to interrupt the HHC when the blade load increases above a certain threshold. The vibration of a helicopter cockpit caused by the first bending mode of the helicopter tail ("tailshake") can be cancelled by blade pitch control of the tail rotor [1579]. Tailshake can also be diminished by an active mass damper [1580] or by active two-mass dampers as a cascade structure where the upper resonance system can be frequency-adjusted to follow varying excitation frequencies [1581]. Helicopter fuselage vibrations caused by the driveline can be cancelled by collective blade pitch control of the main rotor [1582]. Helicopter vibrations can also be reduced by an active mass damper mounted on top of the main rotor hub [1583]. A variable power transmission device for a helicopter is disclosed in , [1584]–[1587], not only enhancing fuel efficiency but also reducing the noise level; the rotational speed of the main and tail rotors is continuously varied while the engine rotates at constant frequency. Active vibration control of a convertible tilt rotor aircraft by control surfaces at the trailing edge of the wings is disclosed in [1588]. Active vibration isolation of the helicopter fuselage from the main rotor system is possible by connecting the two structures through electro-hydraulic actuators driven by a feedforward controller with rotor-mounted accelerometers as reference transducers [1589]. An electro-hydraulic strut assembly has been disclosed earlier by the same assignee [1590]. Also a series of Sikorsky patents aims at reducing the in-cabin noise of helicopters by active vibration isolation of the fuselage from the gear box [1591]– [1592].

Resonance vibrations in a *gimbal structure* can be damped by a servo loop feedback controller acting on a torquer positioner [1593]. Active feedback control of lateral *rail vehicle* vibrations with pneumatic or hydraulic actuators is proposed in [1594, 1595]. AVC for an *elevator cab* is described in [1596]. Structural damping can be enhanced by energy transfer from lower to higher vibrational modes via stiffness control, since the dissipation loss is increased [1597]. Wave-induced vibrations in a *ship's hull* can be reduced by sort of a tuned mass damper where the mass is represented by a chain locker (including the chain) and/or other ship equipment and cargo [1598].

A narrowband compensator of structural vibrations follows the classical compensator/regulator approach with adaptive frequency adjustment [1599]. Resonances of structures with hydraulic devices can be suppressed by actively controlling a hydraulic valve [1600]. Bending and torsional vibrations of *snowboards* and *skis* can be damped by piezoelectric actuators embedded in the board, either by a resistive shunt or by an active feedback controller [1601].

The *squeal* of vehicle *disk brakes* can be cancelled by piezoelectric transducers in a feedback loop [1602], or, according to [1603], by active impulse excitation of the brake structure (in this patent text "actuators" are termed "sensors"). An active vibration damper for automobile drum brakes is disclosed in [1604, 1605], applying piezoelectric sensors and actuators in a feedback control loop to avoid brake squeal. An active disk brake controller with magnetostrictive actuator acting directly on the hydraulics is disclosed in [1606]. An anti-skid braking system for road vehicles is described in [1607], evaluating speed sensor signals from each wheel and controlling the pressure applied to each brake cylinder, and simultaneously reducing drive train vibrations.

Torsional and longitudinal tape vibrations in a *cassette recorder* can be damped by a limited angle torquer electromotor acting upon a supply tension arm of the tape transport; the tape vibrations result in a back EMF in the motor which is used in a servo control mechanism to damp the vibrations [1608].

Acceleration reduction in *reciprocating machines* such as direct-acting Stirling engines is possible by an appropriately driven auxiliary mass [1609, 1610]. Vibrations of a reciprocating gas compressor are greatly reduced by the application of magnetic bearings [1611]. The power output of a free piston Stirling engine can be matched to the power demand by a variable gas spring, thereby also accomplishing vibration reduction [1612]. Active dampers for a Stirling engine preventing externally excited (and possibly damaging) resonance vibrations in the engine are described in [1613] and [1614]. An adaptive feedforward AVC system for a Stirling engine working as a cryogenic cooler in spacecraft is disclosed in [1615]. Vibration cancellation of the compressor of a refrigerator with a non-pollution gas as coolant is outlined in [1616], constructing it such that the piston of a reciprocating linear motor and the vessel vibrate in antiphase so that no net vibration of the compressor results.

Unbalance control for the platform of an inertial guidance system, which carries a dithered ring laser gyroscope, is obtained by a controlled countermass [1617].

Active damping of *spacecraft* appendages such as solar arrays can be accomplished, for several vibration modes, by one three-axial inertia-wheel torquer [1618]. Slewing maneuvers of flexible spacecraft with jet control can be performed in minimum time without residual vibrations by applying positive and negative accelerations in a special pulse sequence [1619]. Active (smart) damping patches for vibration control of, e. g., spacecraft truss structures comprising piezoelectric transducers are disclosed in [1620] and [1270]. Vibration control of spacecraft antennae is possible by inserting electrorheological or magnetorheological dampers in the cables connecting the antenna dish with the spacecraft [1621]–[1623].

Dynamic absorbers for, e. g., plate vibrations with electromagnetic actuators and adjustable resonance frequency are disclosed in [1624]. A dynamic vibration absorber with an electrodynamic actuator serving as an active mass damper supports a conventional engine mount [1625]. Vibration transmission control between structures by an attached dynamic absorber is suggested in [1626] where either the mass of a fluid-filled cavity or the stiffness of an air spring are controlled to tune the absorber resonance frequency to the vibration frequency. Periodic aircraft fuselage vibrations can be reduced by a dynamic absorber the resonance frequency of which is adaptively tuned to the structural vibration frequency, by adjusting the spring stiffness of the mass/spring absorber [1627, 1628]. A decentralized adaptive dynamic vibration absorber for application to engine mounts is disclosed in [1629], employing a modified filtered-x LMS algorithm, yet without the need of plant modelling, and being effective for both tonal and broadband vibrations.

Vibration-induced sidebands of *quartz oscillators* can be actively cancelled by applying a compensation signal to the electrodes [1630]. An electromagnetically tuned vibration absorber serves as tracking absorber by impedance adjustment, including resonance suppression [1631]. Precision position control of *microscope lenses* is possible with piezoelectric bending actuators, thereby also providing vibration reduction [1632]. Vibration-induced electron beam aberrations in scanning electron microscopes can be cancelled to improve image quality [1633, 1634]. Vibration cancellation of images from microscopes with long viewing distance, as used in surgery, is possible by lateral shifting actuation of a lens [1635]. The *motion unsharpness* of pictures taken with a camera can be reduced by controlling the lateral position of one lens group, in response to a vibration detector and an object distance detector [1636, 1637]. Noise and vibration of a *vibratory feeder* can be cancelled by AVC acting on the support frame [1638] or by a loudspeaker mounted such that the canceling sound is radiated from a ring slit around the vibratory feeder , [1639]–[1641].

An *electrorheological gel* with contacts in form of interdigital metal fingers provides an electrically controllable shear stiffness which can be used as a vibration damper [1642] where, in contrast to electrorheological fluids, the polarizable particles do not tend to settle to the bottom of the housing. A *magnetorheological gel* is described in [1643] and [1644].

Electrical machines which vibrate with the power line frequency and higher harmonics can be controlled by shakers acting on the housing [1645].

An *optical interferometer* with active compensation for external vibration or air turbulence is the subject of [1646] where interference fringes observed by a CCD camera are used to drive three PZT elements which support a reference plate. Optical scanners of data storage devices such as CDs, DVDs etc. sometimes suffer from howling due to mechanical resonances of the support plate; the resulting signal distortion can be compensated by active digital control employing a phase-locked loop [1647].

Vibration reduction in power-assisted *vehicle steering* devices can be accomplished by an electronically controlled friction damper in the hydraulic system [1648].

In modern electronic *circuit board* assembly machines a gripping device is moved in the x-y plane by a servo-driven carriage, a gantry beam, which tends to vibrate; in [1649] a velocity feedback control device is described which cancels the vibration and thereby improves the positioning precision. Active position and vibration control for precision equipment such as a bed carrying microelectronic wafers which are moved stepwise between short light exposures is disclosed in [1650], providing pneumatic leveling control of the wafer support. High-speed, high-accuracy position control is also the subject of [1651], intended for applications in machine tools, semiconductor exposure devices, optical alignment etc., by damping the bending vibrations of a cantilever bar actively with piezoelectric actuators.

Comparatively new fields applying the AVC technology are *active optics* and *adaptive optics*. Initially developed for large astronomical telescope mirrors, active optics served to correct mirror deformation under its own weight by an array of (typically hydraulic) actuators attached to the rear side of the mirror. While this quasistatic multichannel shape control system did not present major control problems, adaptive optics aims at correcting for the image blurring by atmospheric turbulence (the so-called *seeing*) with frequencies up to 1 kHz. For this purpose, usually the secondary mirror surface is controlled by a piezo array so that a natural or artificial "guide star" yields a sharp image. An application of active optics in ophthalmology is disclosed in [1652] where an active mirror serves to adjust the focus plane of a laser beam to specified inspection layers in the eye. An application of this technique to laser machining is described in [1653] where an active optical mirror serves to optimally focus a laser beam to the desired spot. Similar devices for controlling the divergence of a laser beam for machining are described in [1654] and [1655]. An adaptive mirror system for the illumination device of a semiconductor wafer stepper is disclosed in [1656]. A microscope with adaptive optics is disclosed in [1657] where the wavefront modulator is located between the objective and tube lens or in the illumination path; further possible applications are a laser scanning microscope and confocal microscopy.

17. TRANSDUCERS

Many ANC and AVC applications require specifications which are not met by conventional sources such as loudspeakers, shakers etc. so that special devices have been developed. The same is true for acoustic and vibration sensors. Patents describing heat protected and heat resistant loudspeakers have been listed in Section 3. More patents on transducers are presented in the following.

An electropneumatic *loudspeaker* for high-intensity sound reproduction is based on a modulated air stream, produced by an electromagnetically controlled oscillating flap [1658, 1659] or valves in a variety of constructions [1660], the latter one employing an overpressure chamber and an underpressure chamber to ensure better symmetry of the oscillating air stream. An ionized gas stream, passed across spaced electrodes, can be used as a sound source by appropriate modulation of an electric d.c. current through it. The use of this phenomenon to actively suppress combustion instabilities has been mentioned in Section 11. The patents [1661], [1215], [1216] and [1662] recommend such systems also for sound reproduction at extremely high sound levels without a conventional loudspeaker.

A variety of *unconventional sound sources* for application in ANC systems have been proposed by O. Bschorr: hot wires, electric arcs, magnetohydrodynamic actuators, pneumatic sources, sirens, pulsed fuel injection to exhaust pipes [14], as well as hydraulic elements and controlled light absorption [15]. Similarly, for AVC applications, Bschorr has proposed (besides electrodynamic systems, magnetostrictive and electrostrictive actuators) hydraulically or pneumatically driven membranes, controlled air cushions, and induction by the geomagnetic field [16], and furthermore active impedance control [1663]. A siren with resonance chambers for improved efficiency is disclosed in [1664] where also a three-siren source is described to create a rotating sound field for the cancellation of spinning modes of propeller aircraft etc. A method to produce anti-sound by excitation of plasma oscillations has been mentioned in Section 4.5 [523].

A tripole source serving as an active sound absorber in a ventilation duct is described in [1099]. Direct sound generation from digital signals, without digital-to-analog conversion (DAC) and power amplifier, is possible according to [1665] and [1666], the latter one employing position control of the speaker cone with an error propagation technique. A digital earphone with feedback ANC to cancel ambient noise is disclosed in [1667], employing in a lightweight earcup a small electret microphone for the feedback loop and several equally small electret loudspeakers to reproduce the input signal and the noise cancellation signal. A high-intensity sound source, intended for application to an acoustic refrigerator, is described in [1668]: an electrodynamic actuator is mounted in a compressor chamber and driven at the common resonance frequency of actuator and chamber so that a pulsating gas stream is released from the outlet valve of the compressor chamber. A "rod radiator" is disclosed in [1669]: a conventional transducer is attached to a mechanical waveguide exciting structure-borne sound which drives a phased array of local radiators so that an endfire array results; a variety of possible realizations is presented, and the radiator is said to be adjustable to a broad frequency band and a wide range of impedances, directivities, efficiencies, and shapes. Pressure pulses out of and into a reservoir can be controlled to serve as a high-intensity low-frequency sound source, both for radiating and actively absorbing sound [1670].

Modulated air flow can serve as a low-frequency dipole source [1671] or cancel pressure fluctuations in the outlet of aircraft jet engines [1114]. A loudspeaker system with dry air ventilation has been developed for ANC applications in wet surroundings [1672]. Flat panel mid and high frequency band loudspeakers for both ANC and entertainment systems in vehicles use piezoelectric patches acting on flat plates in shallow casings or directly on selected areas of the cabin trims or liners [1673, 1674, 1675, 1676, 1677, 1678]. A photo-thermo-acoustic device is described in [1678]: several focused laser beams heat a gas volume periodically to create a distributed sound source, with possible applications to sound shielding etc. A conventional loudspeaker for ANC duct systems, having frequency response irregularities, can be turned into a constant-velocity source by current feedback control [1679]. A loudspeaker specially designed for application in windows with double glazing is disclosed in [1680].

Actively tuned Helmholtz resonators can serve as sound absorbers for a wider frequency band than conventional resonators [336, 1681, 1682], and multiple piezoelectric transducers acting on one Helmholtz resonator provide an intense ANC sound source [1683].

The loudspeaker *frequency response function* can be improved by resonance suppression with a simple delay-and-add circuit [1684], or by motional feedback [1685, 391, 1686, 1687]. Instead of conventional motional feedback, a spider-less loudspeaker design is proposed in [1688], the loudspeaker cone being held by a frictionless movable support, and a position sensor signal being used to modify the audio signal so that the desired cone motion is obtained. The acoustic input impedance of a loudspeaker mounted in a wall can be adjusted to desired values by active loading of the electrical terminals, in particular by feedback control of the induced current in a shunt resistor, so that the magnitude and phase of the acoustic reflectivity can be controlled in a wide range, enabling the wall impedance to be varied between absorbing and highly reflective, thus providing a room with variable acoustics [1689]. In [1690] a loudspeaker box is described with resonance suppression by a second electrodynamic system in the rear part which serves as an active absorber by impedance control with a pressure sensor, a velocity sensor and feedback control. Similar systems are disclosed in [1691] and [1692], offering a variety of control strategies for the backing loudspeaker and various types of frequency response functions.

Means for overload prevention of loudspeakers have been mentioned repeatedly in former sections: [110, 119, 142, 143, 181, 367]. Loudspeaker distortion can be corrected by a nonlinear network [1693], by adaptive feedback model reference control [1694], by motional feedback [1695], or an adaptive feedback system controls a precompensation filter to mimic the inverse loudspeaker transfer function [462]. Nonlinear signal distortion by a phonograph can be compensated by a negative feedback amplifier with a replica of the nonlinearity in the feedback path [1696]. Compensation of linear and nonlinear distortion of an actuator by a controller and a parameter detector is the subject of [1697], serving both for linearization of the transfer function and overload protection. A loudspeaker designed for high output power, as for ANC mufflers of automobiles, is presented in [1698], providing a d.c. voltage to compensate for a deviation of the membrane from the center position at high excursions.

A variety of actuators for the active control of unsteady motion phenomena of turbomachinery are proposed in [1315] besides the conventional loudspeakers and piezoelectric transducers: fluid suction or injection with valve or flap control, and thermal control by electrical discharges or laser pulses.

A piezoelectric actuator with electromagnetic feedback damping is suited as source of short pulses, e. g., for distance measuring devices [1699]. An electromagnetically driven mass can serve as a low-frequency vibrator [1700]. An electromagnetic AVC actuator for axial vibration of a mass shows linear response over a large stroke [1701]. An electromagnetic actuator with sawtooth-shaped pole pieces which are filled with an elastomeric material provides oblique actuation [1702]. A piezoelectric precision actuator with servo control or feedforward control is disclosed in [1703, 1704, 1705]. The feedthrough capacitance of a piezoelectric sensoriactuator can be compensated for by an adaptive feedback control system; this can be utilized for health-monitoring of the actuator [1706]. An electromechanical film transducer (sensor or actuator) is described in [1707], consisting of electret foils folded such that air cushions are formed which change their square cross section to a rhombic shape when actuated. Combination of two such layers with opposite poling yields a bending actuator.

A *microphone* to be built into tape recorders etc., with reduced sensitivity to structure-borne sound, combines an electret microphone with a piezoelectric vibration sensor, the output of the latter being subtracted from that of the former [1708]. A two-dimensional microphone array for auditorium and teleconference applications is disclosed in [1709] and provided with a signal processing arrangement that allows several beams of microphone directivities to be adjusted to arbitrary speaker directions, thus avoiding voice signal distortion by noise and reverberation. A microphone for use in a vibrating environment (such as a vehicle) includes an accelerometer the output of which is used to remove he vibration-induced component from the microphone signal [1710]. Microphone probes for flow ducts with suppression of turbulent pressure fluctuations by long porous tubes have been described in [1711, 1712]. Directional microphones for an adaptive noise canceler are outlined in [1713], and a two-microphone system with directivity enhancement by adaptive noise canceling in [1714]. A two-microphone system for adaptive speech enhancement in hearing aids is disclosed in [1715], adaptively steering the highest sensitivity to a speech source and null steering to a disturbance source (which must be in another direction); the signal processing is performed in the frequency domain. A noise canceling microphone to be used by motorcycle riders is disclosed in [1716]. ANC or AVC sources with fluidic amplifiers are the subject of [1717, 1529, 1530]. Turbulence noise can be removed from microphone signals taken in strong air or liquid flow by an adaptive ANC strategy, utilizing the different correlations of acoustic signals and flow noise in a microphone array [1718], [1719]. Directional (instead of omnidirectional) microphones are often used when suppression of ambient noise is necessary. This effect can be enhanced further by combining two gradient-type microphones to a second-order spatial derivative assembly, e. g., for a telephone handset where speech pauses are used to update an adaptive filter which minimizes the output due to ambient noise [1720]. A microphone system consists of six microphones flush mounted on a small sphere; its cardioid characteristic can be steered electronically into any direction by taking pairwise sum and difference signals, filtering, weighting, and delays [1721]. Two cardioid microphones with variable gain and fixed delays can be combined to derive a variety of directivity patterns, in particular to track or null moving sources [1722].

Distributed one- and two-dimensional sensors (and, analogously, actuators) for the active control of structural vibrations and sound radiation are discussed in detail in [1723], including piezowires, PZT and PVDF foils, without and with shaping for modal sensing and modal control, and including the Frost algorithm for rapid convergence to minimum power radiation.

A torque actuator which consists of parallel rods exhibiting warping under longitudinal forces is disclosed in [1724].

A combined acceleration and sound pressure sensor is presented in [1725], consisting of an annular foam electret sound pressure microphone with an accelerometer inside the ring which consists of another electret foam transducer with a mass on top; the device may be used for ANC systems of the

JMC type (see Section 1).

A capacitive accelerometer with a silicon plate is outlined in [1726]. Fiber optic devices can be used as strain sensors [1727]; with two fibers one of which serves as an unloaded reference, an interference fringe counter can be applied [1728]. A fiber-optic vibration sensor is insensitive to electromagnetic interference [1729, 1730, 1344]. An optical microphone is disclosed in [1731], consisting of a laser, a beam splitter, a multiply light reflecting path (two parallel mirrors) where one of the partial light beams undergoes a Doppler shift if a sound wave travels through the light beam field, and a photodetector to superimpose the modulated light beam and the unmodulated reference beam from the beam splitter. Demodulation is performed by conventional heterodyning methods.

A damping layer is disclosed in [1732, 1733, 1734] in which piezoelectric particles convert vibrational in electrical energy, the latter being dissipated in carbon fibers serving as resistors.

Adaptive (smart) structures with embedded sensors and actuators are subjects of great research interest, for applications in a variety of fields. Active cancellation of underwater self-noise received by a submarine's sonar system is achieved by a multilayer composite coating, comprising PVDF layers as sensor and actuator, separated by an absorber layer [1170]. An adaptive coating for active sound radiation suppression from underwater structures comprises an inner actuator layer of, e. g., piezorubber and an outer sensor layer of, e. g., PVDF. Appropriate signal processing allows the adaptation of the acoustic input impedance to prescribed values such as perfect absorption [1735]. Actuators with large stroke can be constructed from a curved plate by an active coating with a layer of piezoceramic or piezopolymer, electro- or magnetostrictive material, shape memory alloy, electro- or magnetorheological fluid or the like, so that electrical, magnetic or thermal actuation causes a lengthwise variation of the active layer and hence a bending deflection of the composite plate, which translates into a longitudinal excursion with larger stroke if the plate is curved into a semi cylindrical shape [1736]. An active coating as electrically adjustable sound absorber in form of "acoustic tiles" for, e. g., submarines employs electrorheological (ERF) or magnetorheological fluids (MRF) so that the sound velocity and, hence, the acoustic impedance can be adjusted, possibly in combination with an active diffuser structure [1737]. An autonomous system for damping structural vibrations is disclosed in [1738]: several piezoelectric and magnetostrictive transducers are attached to the structure, so generating electricity which can either be dissipated (adaptive passive control) or fed to some of the transducers to counteract the structural vibration.

A particularly silent brushless d.c. electromotor results from a special design of the magnets of rotor and stator [1739].

The following list relates the abbreviations to the countries, and gives the numbers of primary and total patents for each country.

Abbrev.	Country	primary	total
AR	Argentina	0	1
AT	Austria	1	102
AU	Australia	5	199
BE	Belgium	2	19
BR	Brazil	0	33
CA	Canada	3	346
CH	Switzerland	3	12
CN	China	0	30
CS	Czechoslovakia	3	3
CZ	Czech Republic	0	3
DE	Germany	183	630
DK	Denmark	2	21
EE	Estonia	0	4
EP	European Patent	66	755
ES	Spain	0	61
FI	Finland	13	33
FR	France	79	158
GB	United Kingdom	105	241
GR	Greece	0	3
HK	Hong Kong	0	8
HU	Hungary	0	7
IE	Ireland	0	3
IL	Israel	1	15
IN	India	0	1
IT	Italy	13	46
JP	Japan	455	864
KR	Republic of Korea	6	45
LU	Luxembourg	0	2
MX	Mexico	0	8
NL	Netherlands	10	33
NO	Norway	1	37
NZ	New Zealand	0	4
PL	Poland	0	9
PT	Portugal	0	1
RU	Russian Federation	0	6
SE	Sweden	10	34
SG	Singapore	2	13
SU	Soviet Union	2	2
US	United States of America	1019	1555
WO	International Patent	76	387
YU	Yugoslavia	0	1
ZA	South Africa	0	13

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[1] Notice: Patents are cited in short form: Inventor(s) (Assignee). **Patent title**. Primary Patent Number and Dates. Related Patents: often Country abbreviations only (see p. 51). In the following listing, Non-English original patent titles are replaced by English translations, noted in [...]. .

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