Brief Introduction to Active Noise Control

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***Abstract* - This paper is a very brief introduction to the field of active noise control. The concept of active noise control based on destructive interference of sounds is presented. The need for high amplitude and phase accuracy of cancelling sound for efficient cancelation is shown. Considered is the possibility of noise cancelation in open and closed space. Quiet zone formed in the local noise cancellation related to the noise wavelength is illustrated. Most important approaches used for active noise control such as the feedforward, feedback and hybrid method are laid out. Adaptive feedforward and feedback structures based on adaptive filtering are outlined considering the influence of secondary path transfer function and acoustic feedback. Suitability of particular methods for different sound characteristics like broadband and narrowband noise and availability or absence of the reference signal is considered. Synchronized waveform synthesis is also presented as a solution for active control of periodic noise commonly produced by rotating machinery. General directions for digital implementations such as choice of sampling rate, adaptive filters length, computational cost, circuits for pre-filtering and post-filtering of reference, error, and secondary signal are given. Some typical applications are listed.**

Keywords - active noise control; feedforward; feedback; hybrid; waveform synthesis

I. Introduction

Quite often in living and work environments, one encounters annoying sounds. The common goal is to reduce noise to acceptable levels. Traditionally, noise reduction is achieved by passive methods, [1]. This involves the use of sound isolating and sound absorbing materials and reactive devices such as Helmholtz resonators or its combination like in reactive dissipative mufflers. However, passive methods are mainly effective at higher frequencies. Active Noise Control (ANC), [2]-[8] is a method for reducing of unwanted noise by generating an acoustic signal of same amplitude but the opposite phase that interferes with the originating noise. Terms Active Noise Cancellation and Active Noise Reduction (ANR) are also used. It is best suited for noise dominated by low frequencies, where passive methods are not efficient. History of developments in an ANC field is given in [9]. Operating range of active and passive methods is shown in Fig. 1. Passive and active methods should not compete but complement each other.

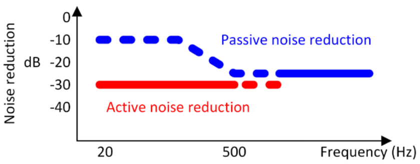

Figure 1. Operational range of active and passive noise reduction

II. Active Noise Control

Operation of ANC systems is based on the principle of destructive interference between sound fields of noise and controlling sound produced by the secondary source, [2].

A. Destructive Interference

Destructive interference is illustrated in Fig. 2. Primary noise and cancelling sound from the ANC system should cancel each other. Noise and cancelling sound should be of equal amplitude, but the opposite phase, [2]-[8].

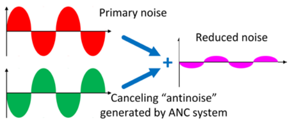

Figure 2. Destructive interference of acoustic signals

B. Active Noise Control System

The ANC system consists of these main components: acoustic sensors (microphones), acoustic actuator (speaker) and controller, [2]-[8], Fig. 3. Noise is picked by a reference microphone and processed by a controller that produces a secondary signal for the actuator. For adaptation controller uses residual noise signal from the error microphone. Important issues are the positions of the reference and error microphone, canceling loudspeaker and adaptation process.

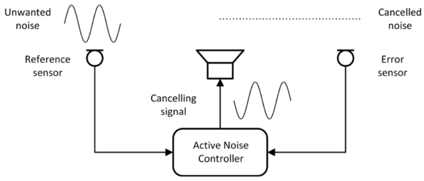

Figure 3. Principle of Active Noise Control

C. Zone of Silence

Significant noise cancelation by a typical ANC system is achieved in a localized region around error microphone, called zone of silence or quiet zone, Fig. 4. Dimension of zone is λ/10, where λ is the wavelength of a noise. Hence, it is easier to form a sizable zone at lower frequencies, [2,4].

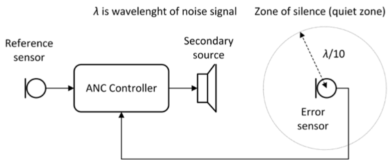

Figure 4. Zone of silence

D. Required Accuracy – Amplitude and Phase Precision

The ANC canceling signal must be very precisely determined to achieve significant noise reduction. If noise pressure is described by (1) and canceling sound pressure by (2), its vector sum is given by (3), where *A* is amplitude,

$$p_1 = A\sin(\omega t) \quad (1)$$

$$p_2 = -(A + a)\sin(\omega t + \theta) \quad (2)$$

α amplitude error and θ phase error of canceling sound, [2]. Data in Table I (dB) determined by (3) illustrates how small amplitude and phase deviations of ideal cancelling signal quickly diminish the noise reduction of ANC system, [2].

$$\Delta = 10\log\left[4\left(1+\frac{a}{A}\right)\sin^2\frac{\Phi}{2} + \left(\frac{a}{A}\right)^2\right] \quad \text{(dB)} \quad (3)$$

TABLE I. NOISE REDUCTION VS. CANCELING SIGNAL ACCURACY

a/A	Φ (°)						
	0	1	3	10	20	30	36 (λ/10)
0	∞	35.0	25.5	15.2	9.2	5,7	4,2
0,005	46	33.7	24.4	15.1	9.2	5,7	4,2
0,05	26	25.7	22.6	14.2	9.0	4,8	3,9
0,10	20	19.8	18.6	13.6	8.6	4,0	3,7
0,20	14	14.0	13.6	11.0	7.6	2,8	3,4

E. Cancellation of Periodic and Broadband Noise

Periodic noise consists of periodically or quasi-periodically distributed repetitive waveform patterns. It has a harmonic structure and is generally deterministic. An example of such noise is a sound field generated by rotating machinery, engines, electricity humming noise and devices driven beyond their capability. Broadband (or wideband) noise, has sound energy that is distributed over a wide part of the audible range as opposed to narrowband noise. Such noise is often stochastic, has a wide range of wavelengths including short ones and as such is much more difficult to attenuate. In the real world, both types of noise come together with various relative contributions. Broadband noise superimposed on periodic noise is shown in Fig. 5.

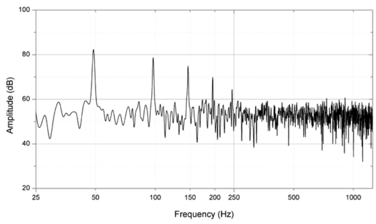

Figure 5. Tonal noise with superimposed broadband noise

F. Cancellation at Source

The preferable method of noise reduction is the reduction of noise at source, as shown in Fig. 6. [10]. Although, not cancelled at the very point of generation, noise at the output of exhaust duct is reduced before radiated into the environment. However, in most cases, cancelation at (or close to) source is not possible and reduction is achieved in small target zones of silence.

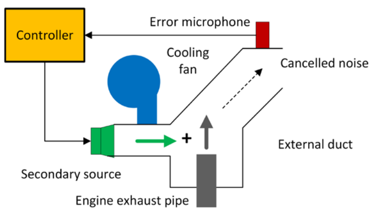

Figure 6. Noise cancellation at source

G. Active Noise Control in Closed and Open Space

1) ANC In Small Closed Space

It is relatively easy to reduce noise within a small closed space like an ear cup of a headphone, Fig. 7, as one doesn't have to deal with spatial sound considerations, [11].

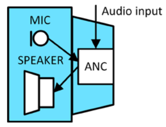

Figure 7. ANC in closed small space (headphones)

Dimensions of an ear cup are small, and zone of silence related to $\lambda/10$ is quite effective up to mid frequency range.

2) ANC Within a Large Closed Space

This task is much more complicated and require more secondary sources. One way is to construct numerous smaller zones of silence at points of interest within a space. Another way is to position secondary sources in corners of the space to counteract acoustical modes, [4].

3) ANC in Open Space

In open space it is possible to use an active acoustic barrier that reduces noise at its path, [2,12,13]. Active control of broadband sound through the open aperture of a full-sized domestic window is illustrated in Fig. 8, [12].

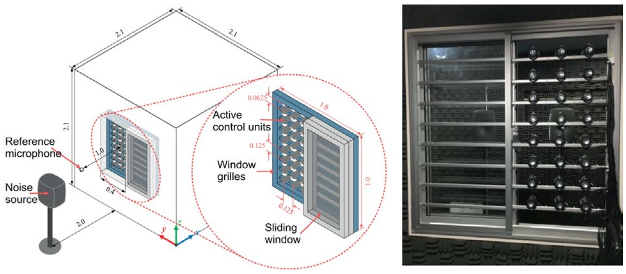

Figure 8. ANC applied to window, [12]

III. ADAPTIVE DIGITAL FILTERING

With the exception of some ANC headphones, almost all ANC implementations today are digital. Algorithms for ANC vary for the particular cancellation strategy, but generally use adaptive digital filters. Block diagram of finite impulse response (FIR) filter, [14] is shown in Fig. 9.

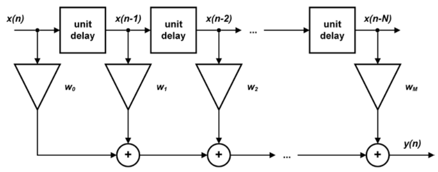

Figure 9. FIR filter

Output of the filter $y(n)$ is given by (4), where w_i are filter coefficients, $x(n)$ input signal, and N filter length.

$$y(n) = \sum_{i=0}^{N-1} w_i\, x(n-i) \quad (4)$$

There also exists infinite impulse response (IIR) filter that is a recursive and is more complicated. Its output depends on the current and previous inputs and previous outputs. However, FIR filters are more widely used. An adaptive filter is a filter with self-adjusting characteristics. The filter coefficients are adapted according to an adaptation algorithm. The most common algorithm is the Least Mean Square (LMS) algorithm, [14], Fig. 10. Adaptation of filter coefficients w_i at the moment n+1 is given by (5) and (6), where μ is a step size, $x(n)$ signal, $y(n)$ filter output, $d(n)$ desired filter output and $e(n)$ and error at the moment of the sample n.

$$e(n) = d(n) - y(n) \quad (5)$$

$$\mathbf{w}_i(n+1) = w_i(n) + \mu x(n)e(n) \quad (6)$$

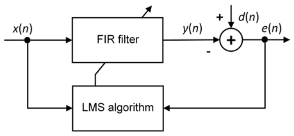

Figure 10. FIR filter with adaptive algorithm

Adaptive filters are relatively simple, but their real-time adaptation requires significant processing resources.

IV. Active Noise Control Structures

The active noise control structures are classified as feedforward, feedback and hybrid structure, [2]-[8].

A. *Feedforward Active Noise Control*

The feedforward ANC approach uses a reference microphone to pick up the noise signal. It also uses the error microphone to measure the residual noise that remains after cancellation. This error signal is used for adaptation in ANC controller.

1) *Broadband Feeforward Active Noise Control*

This approach can be used for cancelling both of periodic and broadband noise. Simplified block diagram of feedforward system, [2]-[8] is shown in Fig. 11.

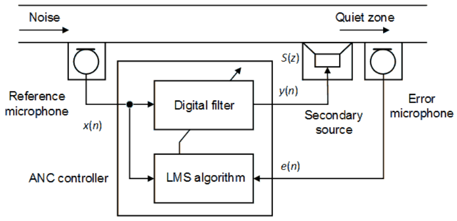

Figure 11. Broadband feedforward ANC

2) *Synchronized Waveform Generator*

This system belongs to the category of feedforward systems. It doesn't use the reference microphone. Instead, tacho signal is picked up by optical or magnetic sensor, Fig. 12. As there is no reference microphone, there is no acoustic feedback and the need for its cancelation. The system is capable of canceling a periodic components of narrowband noise while random broadband component is not canceled. It is suitable for noise with pronounced harmonic content. Waveform samples are stored in a waveform table, (7), [4], L is the period length. These samples are sent in a sequence to the D/A converter to produce a secondary signal.

$$\{w_l(n), l = 0, 1, \ldots, L-1\} \tag{7}$$

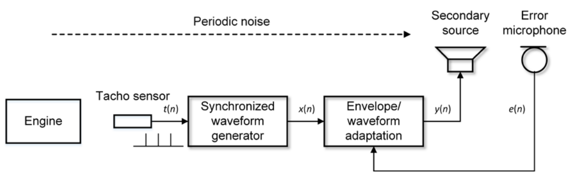

Figure 12. ANC using synchronized waveform generator

B. *Feedback Active Noise Control*

The feedback ANC doesn't have the luxury of reference signal picked by the reference microphone. Instead, it tries to reconstruct the reference signal using the feedback predictor, [2]-[8], as shown simplified in Fig. 13. It can attenuate only the predictable components of the noise. In non-adaptive ANC, filter is fixed. Adaptive system is more

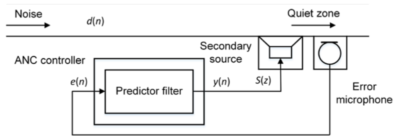

Figure 13. Feedback ANC

complicated and reference signal is estimated as a sum of filtered output and error signal (more details in subsection *D*). The feedback ANC is less robust than feedforward ANC. However, it is more compact and cost effective.

C. *Hybrid Active Noise Control*

Hybrid ANC combines feedforward and feedback control structures, Fig. 14. The feedforward ANC cancels noise correlated with a reference signal. The predictable component of the residual noise that is not present in a reference signal is canceled by the feedback ANC, [4]. Lower order filters may be used in hybrid implementation.

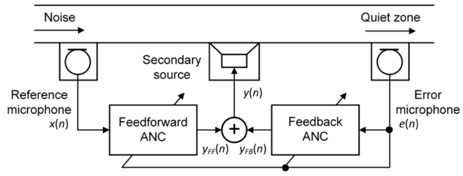

Figure 14. Hybrid ANC

D. *Secondary Path Modeling*

Operation of the ANC system is influenced by the transfer function of the secondary path $S(z)$. This includes D/A converter, reconstruction low pass filter, amplifier, secondary source, acoustic path between the secondary source (sound propagation delay), an error microphone, it's preamplifier, antialiasing filter and A/D converter, [4]. Frequency and phase characteristic of a typical speaker is shown in Fig. 15 and of a typical microphone in Fig. 16. It is necessary to compensate the influence of the $S(z)$, [2,15].

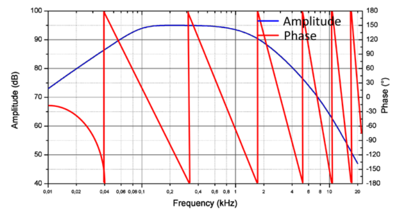

Figure 15. Typical speaker frequency and phase response

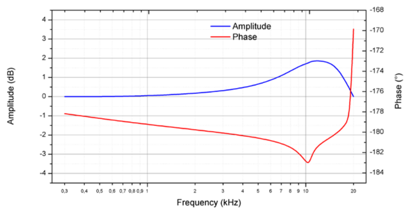

Figure 16. Typical microphone frequency and phase response

To address the influence of the secondary pat, the Filtered-x LMS (FxLMS) algorithm is developed. Instead of signal x, its filtered version x' is used produced by the filter with transfer function $\hat{S}(z)$ that approximates the transfer function of the secondary path $S(z)$, as shown in Fig. 17 for feedforward system and Fig. 18 for feedback system. Adaptation is given by (8), [4]. Estimated reference signal for use in feedback ANC is given by (9), [4]:

$$w_i(n+1) = w_i(n) + \mu x'(n)e(n) \tag{8}$$

$$x(n) \equiv \hat{d}(n) = y'(n) + e(n) \tag{9}$$

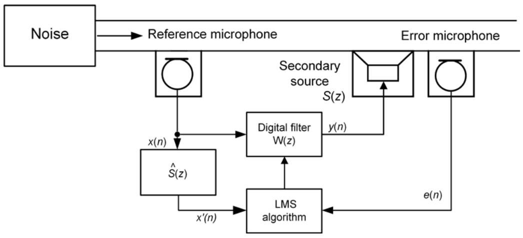

Figure 17. Feedforward ANC using FxLMS algorithm

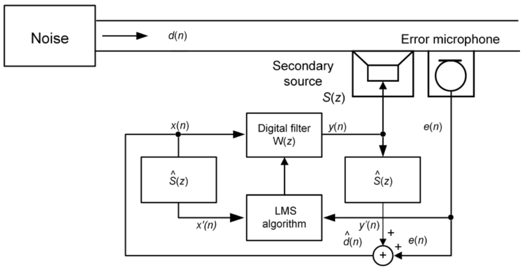

Figure 18. Feedback ANC using FxLMS algorithm

If $S(z)$ doesn't change a lot, it can be estimated off-line, Fig. 19. It is also possible to determine $\hat{S}(z)$ online, by use of additional random noise that is injected to a system after W(z), [4]. Additional LMS algorithm is used to adjust $\hat{S}(z)$.

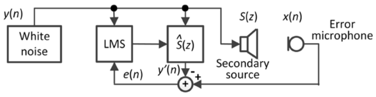

Figure 19. Off-line estimation of secondary path

E. Feedback Cancelation

Canceling "antinoise" signal from the secondary source propagates upstream to the reference microphone and corrupts the reference signal, resulting in an undesired acoustic feedback that may cause instability, Fig. 20. It may be necessary to add a special feedback neutralization filter with transfer function $\hat{F}$ for counteracting the feedback, [4].

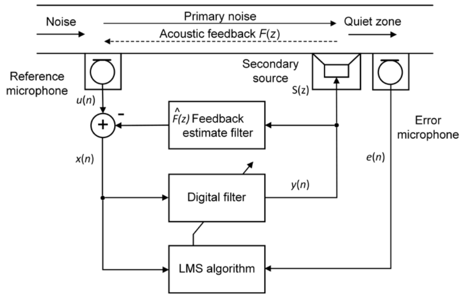

Figure 20. Feedback cancellation

F. Multi-Channel Active Noise Control

Multi-channel ANC employs multiple secondary sources, multiple error sensors and sometimes even multiple reference sensors, as illustrated in Fig. 21. Such system can create multiple zones of silence and is feasible for the attenuation of low-frequency noise fields in three-dimensional space. It tries to minimize the total potential acoustic energy across the space as picked by M error microphones, by minimizing cost function ξ, (10), [4].

$$\xi = \frac{V}{4\rho c^2 M} \sum_{m=1}^{M} {p_m}^2 \quad (10)$$

Fx-LMS algorithm for this system can be expressed in matrix notation, (11),(12). $\boldsymbol{E}$ is error signal, $\boldsymbol{D}$ noise, $\boldsymbol{S}$ secondary path, **W** adaptive filter and $\boldsymbol{I}$ identity matrix, [4].

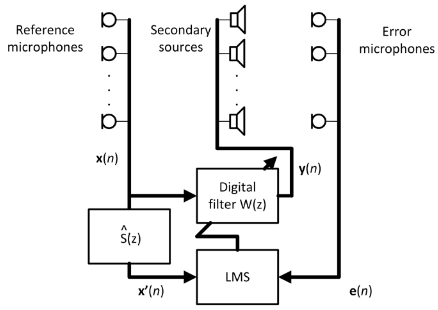

Figure 21. Multi-channel ANC

$$\boldsymbol{E} = \boldsymbol{D} - \boldsymbol{SW} \quad (11)$$

$$\boldsymbol{W}(n+1) = (\boldsymbol{I} - \boldsymbol{\mu} \boldsymbol{S}^H \boldsymbol{S})\boldsymbol{W}(n) + \boldsymbol{\mu} \boldsymbol{S}^H \boldsymbol{D} \quad (12)$$

G. Adaptive-Passive Noise Control

Adaptive-passive (semi-active) noise control uses passive devices whose parameters can be varied to achieve optimal noise attenuation over a narrow band of operating frequencies. Helmholtz resonators (passive devices) are used to used to damp/trap narrow frequency band of noise. They can be, within limits, actively tuned to a different frequency. Two approaches can be used, one, mechanically complex, that modify the geometry of the Helmholtz resonator using the stepping motor, and another that use time-varying feedback Proportional-Integral (PI) controller to tune the natural frequency and damping, [16], Fig. 22.

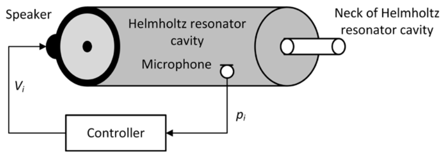

Figure 22. Adaptive Helmholtz resonator

V. IMPLEMENTATIONS

Diagram with the steps for ANC implementation is shown in Fig. 23. Noise from the reference and error sensor is amplified by preamplifiers, filtered by low pass filters and fed to A/D converters. Digital Signal Processor (DSP) implements an ANC algorithm. Values for secondary signal are fed to D/A converter. The analog signal is filtered by a low pass filter and amplified by an amplifier that drives the secondary source. One DSP board with necessary elements for ANC implementation is shown in Fig. 24, [17]. More modern DSP solutions exist, as well as micro-controllers with integrated low latency ADCs and DACs, [18].

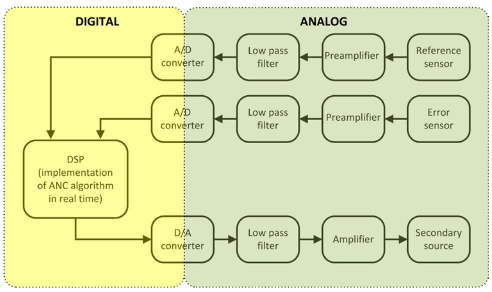

Figure 23. Block diagram of ANC implementation

A. Sampling Rate

Signal processing systems, including ADCs and DACs, must conform to the Nyquist criteria, which states that the signal sample rate must be at least two times greater than the highest frequency component present in the signal.

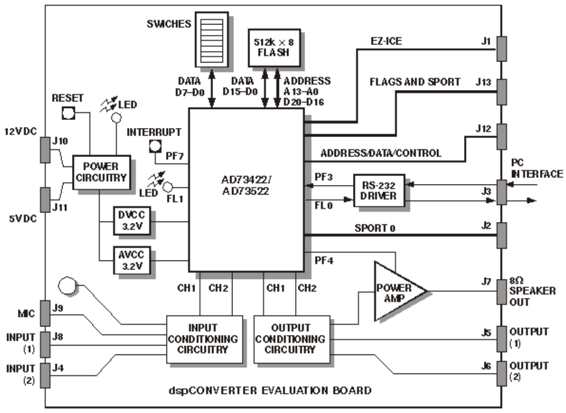

Figure 24. Example of DSP board suitable for ANC (Analog Devices)

However, it is recommended that sampling rate is ten times the target frequency. ANC systems are effective for low frequency noise, hence the required sampling rate may remain low, with manageable processing requirements.

B. *Filter Length*

How long FIR filter to use for $W(z)$ and $S(z)$ in FxLMS implementation? Start with 4-20 taps per tone/harmonic, up to several hundred for cancelling broadband noise, [19]. More taps provide better accuracy, but slows adaptation.

C. *Computational Cost*

Multichannel FxLMS ANC system with I reference inputs, J outputs, K error inputs, L taps for control filter and L_S taps for secondary path estimate must perform the N multiplications and additions per sample, (13), [20].

$$N = IJL + IJK(L+1) + IJKL_S \qquad (13)$$

D. *Filtering of Reference, Error and Output Signal*

Input and output signals should be band-limited by anti-aliasing low pass filters. Classical IC designs with resistor-capacitive (RC) filters are sensitive to component tolerances and temperature stability. The switched capacitor filter allows for very accurate and tunable analog filter to be manufactured without using resistors, [21].

E. *Loudspeaker Sound Ouput*

Speaker used as a secondary source has its sensitivity, a measure of decibel output when supplied with a specified amount of amplifier power. The achieved dB output from an amplifier and speaker combination should match the dB level of the offending noise.

F. *Environmental Influences*

Many practical ANC systems must endure significant vibrations, temperature, humidity and chemical (acid) influences (e.g. engine exhaust mufflers).

VI. Applications

There is a large gap between academic research and effective practical applications. Practical robust ANC implementations that can be commercially exploited are difficult and require synergy of numerous skills: electronics, software, transducer technology and physical acoustics. Key to success is picking applications where it can work.

A. *Active Noise Control Headphones*

The canceling signal is transmitted from the secondary source within the ear cup producing the zone of silence around the ear drum. Analog solution is shown in Fig. 25.

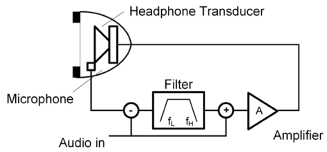

Figure 25. ANC headphones (analog)

There exist open and close loop systems, [11] with microphones positioned outside or inside the ear cup.

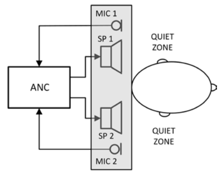

Figure 26. Active headrest

B. *Active Noise Control for Headrests*

The concept can be extended to a headrest, Fig. 26 with secondary sources integrated in a vehicle headrest, [22].

C. *Ventilation Ducts/Heat Ventilation Air Conditioning*

Ventilation ducts and Heat Ventilation Air Conditioning (HVAC) systems must blow enough air through the air ducts. Single channel broadband feedforward ANC system can be efficiently used in ventilation duct, [23]-[25], Fig. 27. There exist two different approaches to installing an ANC in duct applications: (a) microphones and the loudspeaker installed centrally inside the duct, and (b) microphones and the loudspeaker in a separate modules outside the duct.

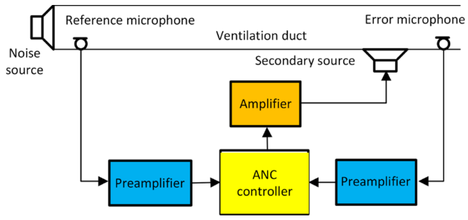

Figure 27. Ventilation duct ANC

D. *Car Interiors*

This includes silencing of car interiors and active engine exhaust mufflers for improved passenger comfort. Car interior noise is affected by engine, road, wind, HVAC and exhaust noise. Ford's ANC solution available on Explorer Limited Hybrid uses strategically placed microphones throughout the cabin to pick up unwanted noise, Fig. 28, [26]. System produce opposing sound distributed through the car audio system. It provides noise attenuation across low and mid-frequency noise.

E. *Interiors of Turborop Aircrafts*

Similarly, ANC is used for reduction of propeller tones (blade pass frequencies), [27]. Achieved results for NVX system applied to King Air aircraft is shown in Fig. 29, [28].

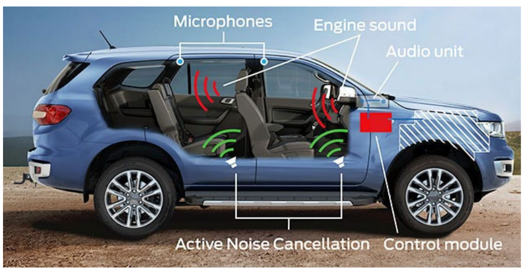

Figure 28. ANC in a SUV vehicle (Ford)

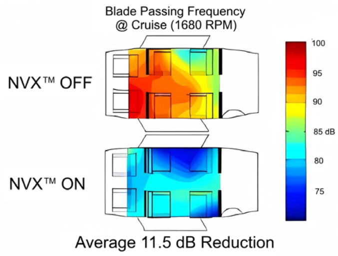

Figure 29. ANC applied to King Air 90 turboprop aircraft (Lord NVX)

Secondary sources in an aircraft are not necessary loudspeakers. Solution with a piezo stack that influences aircraft window is shown in Fig. 30, [29].

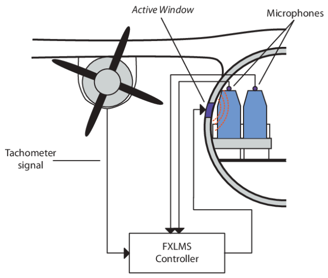

Figure 30. ANC using active window using piezo stack, [29]

F. *Household Appliances*

ANC applied to a vacuum cleaner is shown in Fig. 31, [30]. Passive methods disrupt the airflow and reduce efficiency. Reduction of tonal components have been achieved (about 10 dB), however much less for the entire spectrum (about 2 dB).

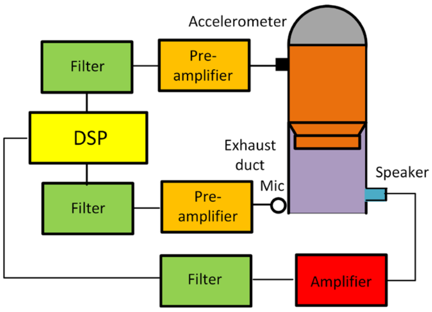

Figure 31. ANC applied to vacuum cleaner

VII. Conclusion

Active noise control has achieved considerable success at attenuating low frequencies, particularly tonal components and forming small local zones of silence. Main ANC control structures are feedforward, feedback and hybrid. These approaches are suitable both for broadband and narrowband noise. The influence of the secondary path in ANC systems has to be addressed and Fx-LMS algorithm was developed for that purpose. It is sometimes desirable to cancel the acoustic feedback as well. The synchronized waveform generator is suitable for cancelling periodic noise, and because of nonacoustic sensor it is not susceptible to acoustic feedback. Multichannel system are suitable for vehicle interiors. Some success has been achieved with semiactive solutions (tunable Helmholtz resonators) as well. Due to the low cost of DSP and microcontrollers, with the exceptions of some headphones, most ANC implementations of today are digital.

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