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RECENT ADVANCES IN THE ACTIVE CONTROL OF STRUCTURALLY RADIATED SOUND

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ABSTRACT

Recent research and applications in the field of Active Structural Acoustic Control (ASAC), a technique for reducing low frequency sound radiation from structures, are discussed. The paper overviews some new advances in the ASAC component and system areas of actuators, sensors, controllers, analysis and optimization. Recent commercial applications of ASAC as well as some promising new uses are briefly outlined.

INTRODUCTION

The technique of Active Structural Acoustic Control (ASAC) in which sound radiation from vibrating structures is controlled by the use of active structural inputs used in conjunction with radiation error sensors has passed a decade of investigation [1]. In the last few years there has been a much increased interest in ASAC with the result that there has been significant advances in ASAC systems and some commercial applications. This paper will review some of the advances and applications. This paper is not intended to be comprehensive, rather, give a flavor of recent developments and directions. For introductory material on ASAC and a description of previous work, the reader is referred to Ref. 1.

The talk is broken up into a discussion of recent work in the main components of an ASAC system (actuators, sensor and controllers). Some discussion is given to the important areas of system analysis and optimization and finally recent commercial applications of ASAC are described.

ACTUATORS

In general, most of the recent work in actuators for ASAC has been based upon piezoelectric thin plate or wafer devices, which can be directly attached or embedded in the structure. These devices tend to be high force, low strain while low frequency active control applications usually require significant displacements from the actuators. Much effort has thus been directed towards increasing the control authority (the strain) of the actuators and directly integrating the sensor into the actuator system. In general, motion amplification is achieved by attaching the piezoelectric wafer to another wafer element or inactive structure as in a bimorph or unimorph configuration [1]. Tip bending then occurs due to differential expansion or off-axis traction loads respectively. More recently, two unique methods of manufacturing such actuators have appeared; the "Rainbow" [2] and the "Thunder" [3]. The Rainbow actuators are manufactured by selectively reducing one surface of the piezoelectric wafer while the Thunder actuators are laminated under heat and pressure. Both actuators are essentially unimorphs, although the manufacturing process results in a domed shape, which also gives some amplification. Another related actuator is a "Moonie" shown in diagrammatic form in Figure 1 [4]. This actuator consists of a piezoelectric stack actuator (PZT) with two half moon shaped metal caps attached to each end of the stack. As the stack shrinks when an electrical voltage is applied, the metal caps are squeezed upwards and because of their curvature, the transverse deflection is greater than the stack. Amplifications of 20:1 over the stack displacement are achievable [4].

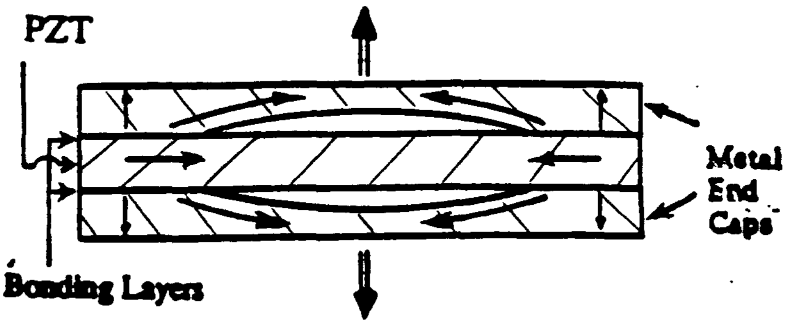


Figure 1. Configuration of a Moonie Acutator [4]

Vipperman and Clark [5] have recently developed a practical piezolectric element which can simultaneously apply traction loads to a structure while sensing its response (termed a "sensoriactuator"). In this approach an adaptive filter is used to estimate the feedthrough capacitance of the piezoelectric device. The mechanical response of the piezoelectric element is resolved from the total electrical response of the element by standard adaptive signal processing techniques. Vipperman and Clark have demonstrated the use of the sensoriactuator on rate feedback control of vibration of a beam [5] and more recently on ASAC applied to a plate (see later).

Effort has been directed towards developing active skins for use in ASAC. In this arrangement the active skin is used to directly change the radiation impedance of the structure in order to control the sound radiation in contrast to the standard approach of altering the structural response. Guigou and Fuller have developed a smart foam in which sheets of the piezoelectric polymer, PVDF, are embedded into passive acoustic foam as shown in Figure 2 [6]. The PVDF can be seen to be curved to achieve motion amplification as discussed above

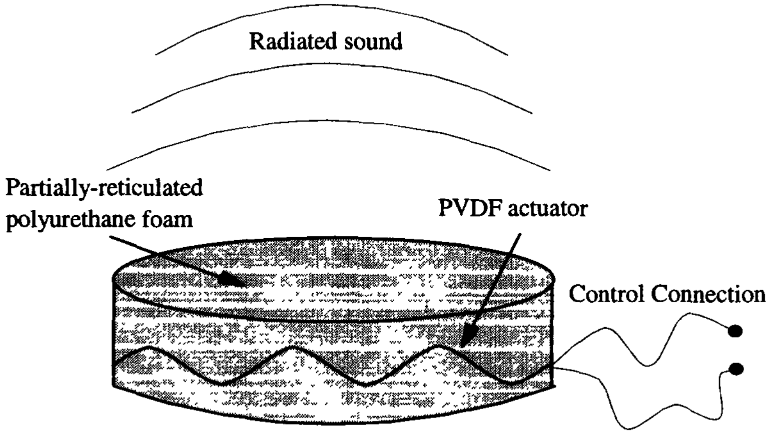
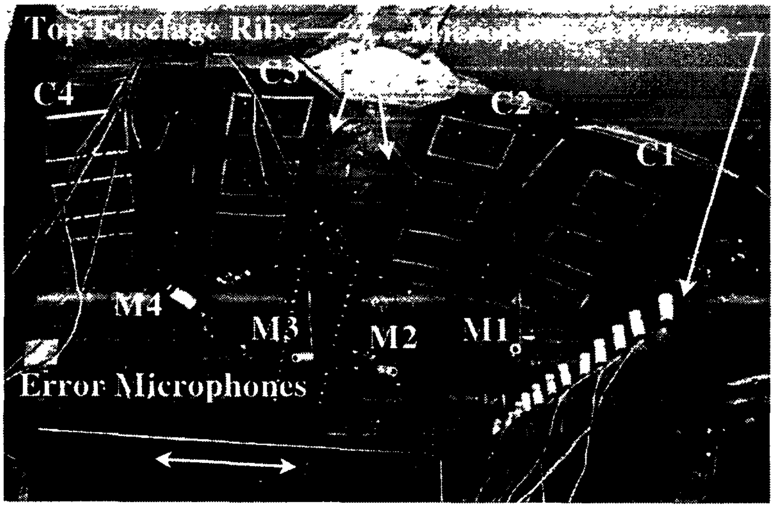
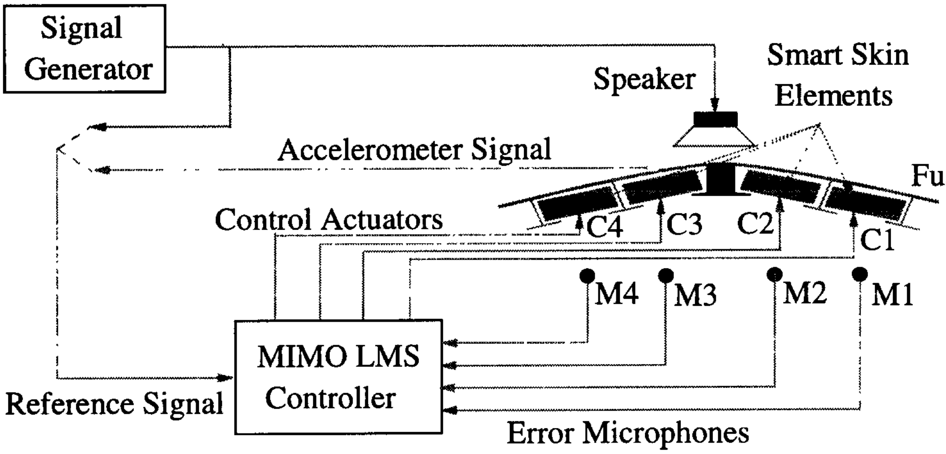


Figure 2. Configuration of smart foam [6]

and alternating sections are wired out-of phase to increase the sound radiation. The radiating structure is covered with the smart foam and control signals are applied to the PVDF in order to minimize sound radiation. The foam also provides structural support for the PVDF and gives significant passive attenuation of sound and vibration. Experiments on using the smart foam for broad band sound radiation into aircraft cabins has shown much potential with attenuations of random noise of 8-10 dB achieved over a 300 Hz bandwidth. The experimental arrangement and control system are shown in Figure 3. In another active skin configuration developed at PSU and shown in Figure 4, unimorph or bimorph piezoelectric actuators are mounted to a base or directly on the structure and are connected with a top cover plate (a double amplification of motion). Thus the small in-plane motor of the piezoelectric wafer actuator is converted into a much larger normal displacement of the cover plate by geometric amplification as discussed above. Amplifications of 25:1 and cover plate displacements of approximately 30 μm at 100 Hz have been measured and a continuous array of the devices (i.e. an active skin) has been used in laboratory experiments to control broadband sound radiation from structures [7].



(a)



(b)

Figure 3. Smart Foam installed in an aircraft cabin for interior noise reduction [6].
(a) Configuration (b) Control System

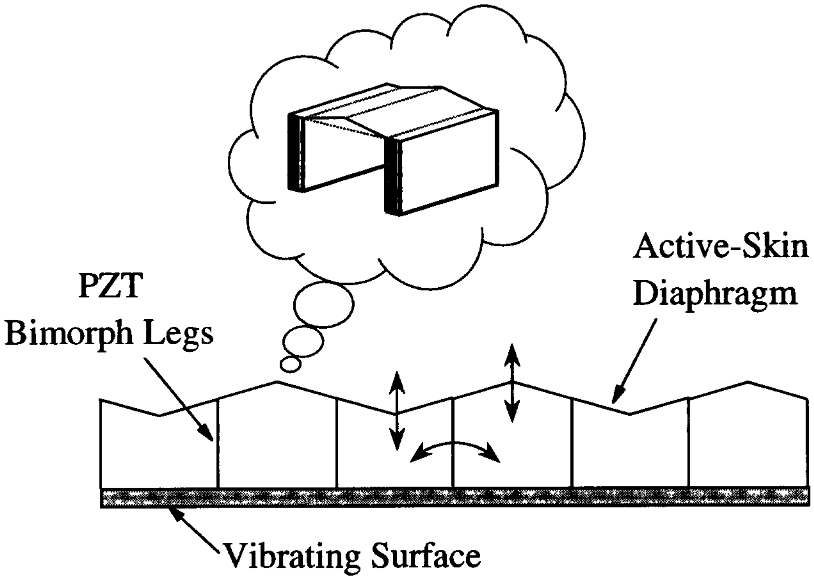


Figure 4. Double amplifier active skin [7].

In a related area, adaptive tuned vibration absorbers (ATVA's) have been used as actuators in ASAC approaches. An ATVA has the capability of adaptively tuning its resonance frequency usually by changing the stiffness factor. Electro- mechanical ATVA's have been used to control sound radiation from structures and it has been demonstrated that the best reduction in sound is when the ATVA's are globally detuned from the excitation frequency [8]. This is achieved by minimizing a radiation cost function and is thus a variant of ASAC [8].

SENSORS

Most recent work in sensors has been directed towards developing sensors which, although integrated into the structure, give an estimate of the radiated sound pressure or power. These approaches can be generally divided into distributed, continuous, shaped sensors and arrays of discrete sensors. A number of workers have developed volume velocity distributed sensors for planar structures [9,10,11]. These sensors are usually cut from PVDF material and are based upon reformulating the sound radiation from the structure into what is known as "radiation modes" [1]. Figure 5 shows an array of volume velocity sensors used to control broadband, low frequency, radiation from a panel [12]. The characteristic quadratic sensor weighting associated with simply supported plate modes is apparent.

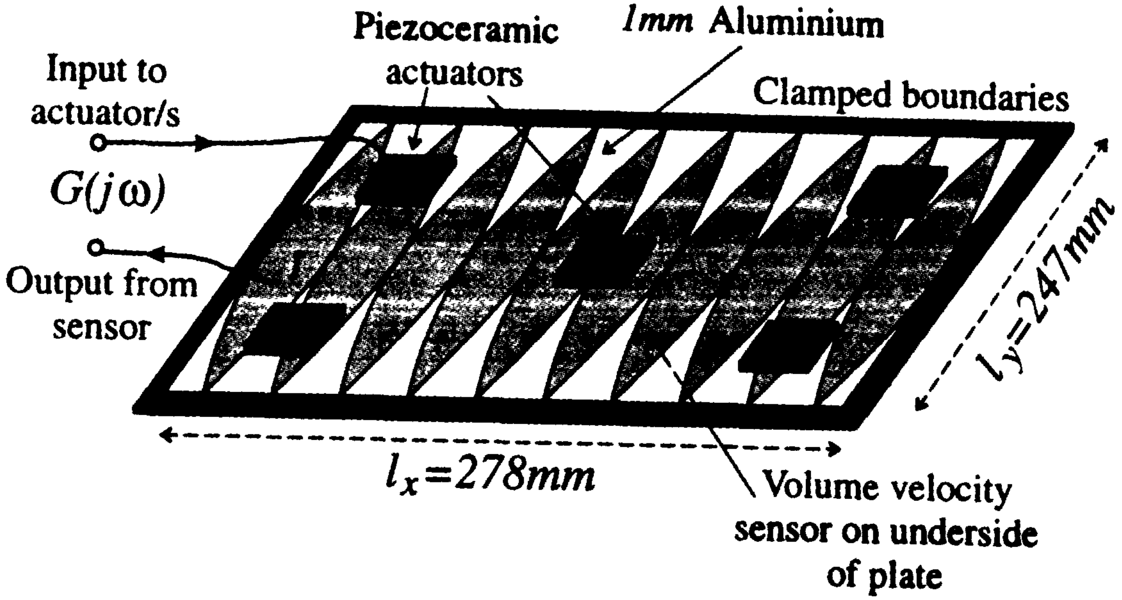


Figure 5. Volume Velocity sensors for control of low frequency broadband sound radiation from a plate [12].

In another approach, Maillard and Fuller [13] have developed a discrete structural acoustic sensing approach (DSAS) in which discrete sensors (usually accelerometers) are located on the structure in an array. The output of the accelerometers are passed through FIR filters which model the structure's radiation Green function [1] and are then summed (c.f the Rayleigh Integral Approach) to give estimates of far-field pressure at discrete angles as shown in Figure 6. These time domain radiation estimates can then be used as error information in ASAC approaches to replace microphones in the far-field as shown in Figure 6.

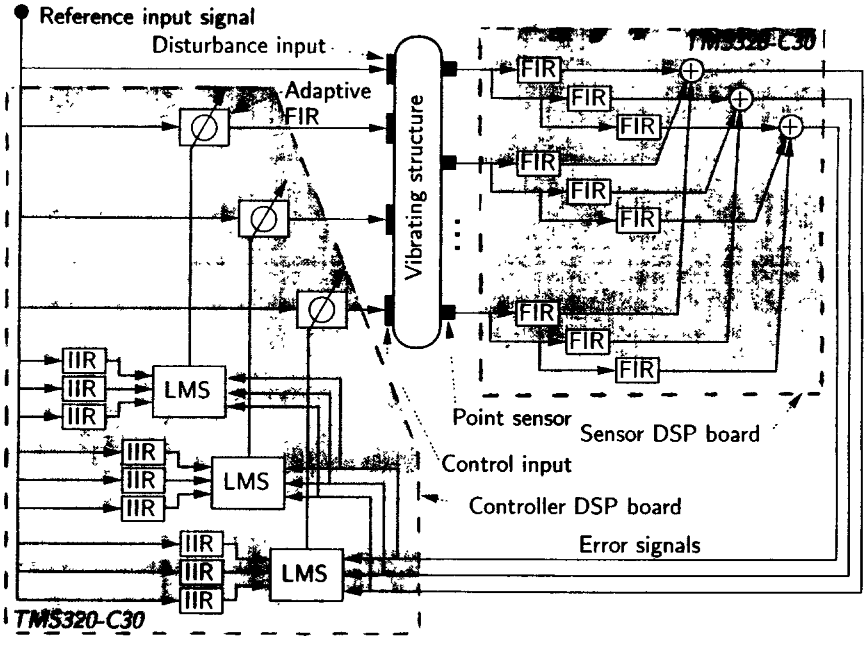


Figure 6 . Discrete structural acoustic sensing used in ASAC of cylinder radiation [13].

CONTROL APPROACHES

Most recent work in ASAC control approaches have been directed towards applying robust, MIMO feedback control approaches to the control of structurally radiated sound. In general, these approaches extend the work of Baumann et al [14] who developed the concept of a "radiation filter" in which structural states are converted to causal, radiation states. Vipperman and Clark [15] have combined multivariable feedback active control with the radiation filter approach of Baumann and the sensoriactuator discussed above to develop a ASAC System, which provides robust control of sound radiation from plates excited by random or transient disturbances. Elliott et al have recently investigated the use of adaptive feedback control approaches based upon the "internal model" control method in which the feedback problem is turned into a feedforward problem using inverse filtering to remove the output of the plant from the feedback loop [16]. These internal model approaches have been recently applied to the control of sound transmission through panels [12].

In other work the feedforward MIMO LMS approach has been extended to well conditioned control approaches which employ a very high number of actuators and sensors. Carneal and Fuller [17] have developed a "Bio" controller in which multiple actuators are controlled in a hierarchical manner. A "master" actuator(s) is controlled by a high level, sophisticated controller (such as a LMS Filtered-x paradigm [1]), while "slave" actuators which are located nearby the master actuator are controlled by simple, local rules(such as phase inversion). The approach, although usually sub-optimal, allows the construction of an adaptive, distributed actuator and has been successfully applied to ASAC systems. Cabell and Fuller [18] have investigated the use of Singular Value Decomposition (SVD) based LMS control approaches which can be used to break the noise field into principle components and used to group individual actuators together into a single channel (i.e. construct a distributed actuator).

In general, analysis of complex, real structural acoustic systems have been based upon using commercially available FEM/BEM packages, [e.g. 19,20]. These codes provide the system frequency response function (FRF) at single frequencies. Usually these FRF's are converted to time domain information by using software [e.g. 21] to construct causally constrained FIR or IIR filters to represent the system impulse responses. The filters can then be used to model the ASAC system dynamics for time domain disturbances (such as random, broadband and transient) and then can be used to investigate the use of various actuator, sensor and control systems using the control theory analysis of Ref. 1 for example.

System identification is also being used in the design of ASAC systems. In general, these techniques concentrate on finding the (usually) small scale structural motions, which are associated with the sound radiation. These small scale motions are often embedded in motions of much larger amplitude which do not radiate effectively, thus making the use of standard identification techniques unreliable. Near field acoustic holography (NAH) is one technique currently being used to identify the structural motions associated with sound radiation [22]. In NAH arrays of pressure measurements are used in conjunction with a wavenumber FFT to predict both the global pressure field as well as the coupled structural motion. An inverse system identification approach has been developed by Paxton and Fuller [23]. In this technique, ANC is used to create the interior field of an aircraft by canceling the interior sound field due to a structural disturbance such as an engine. With the controller locked and the original disturbance removed, the ANC system is used to re-create the (inverse) sound field and drive the structure so as to reproduce only those structural motions that are well coupled to the interior sound field as shown in Figure 7. The normal

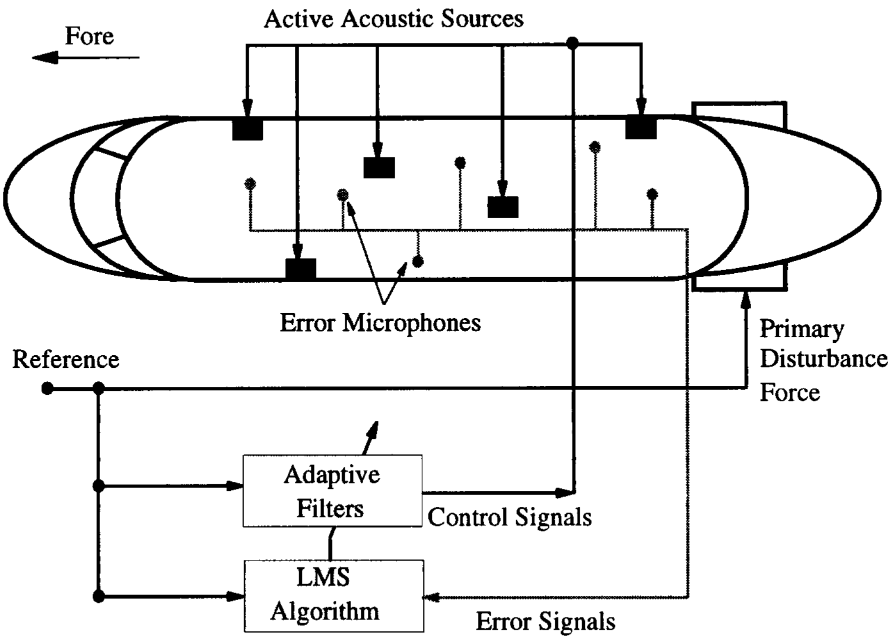


Figure 7. Active noise control system used to reproduce interior cabin field due to a structural disturbance [23].

structural displacement of the fuselage is then measured at an array of points and decomposed into singular values and associated vectors using SVD analysis and are given for an example test in Table 1 [23]. The table shows that the inverse (internal acoustic) excitation results in a lower number of significant singular values and also lower magnitude of singular values (and thus associated vibration). The larger singular values of the internal acoustic excitation indicate the important structural vibration patterns in terms of sound radiation. Optimal arrays of structural actuators can then be designed to excite these dominant singular vectors.

Singular Value	Primary Excitation	Internal Acoustic Excitation
1	3.68	1.59
2	2.81	0.69
3	1.79	0.55
4	1.32	0.41

Table 1. Singular value magnitudes for the disturbance (primary) and internal, locked ANC, acoustic excitation [23].

Once the system has been modeled or identified, then various approaches have been used to optimize the system configuration (generally decide the location, number, shape of the transducers). The most common approach is to measure a discrete number of transfer functions or impulse responses associated with a large number of actuators and sensors. Various discrete optimization techniques, such as genetic algorithms [24] and sub-set selection [25] are used to determine the best transducer configuration based upon a pre-determined performance criterion. Such approaches are an efficient method for determining the best control configuration before expensive, realistic testing begins.

APPLICATIONS

There have been many recent applications of ASAC, most at the laboratory or R & D level. Here we discuss recent commercially available ASAC systems which are being marketed and some which show near term market potential.

An ASAC system has been developed by Ultra Electronics in the UK for control of interior noise in aircraft [26]. In this system inertial electromagnetic actuators are attached to the fuselage frames as shown in Figure 8 and microphones mounted in the trim are used as error sensors. In tests on such a system, applied to a DeHavilland Dash-8 aircraft(propeller driven), the ASAC system showed a significant improvement in control when compared to an ANC system particularly at the higher-harmonics as shown in Table 2 [26]. Many such

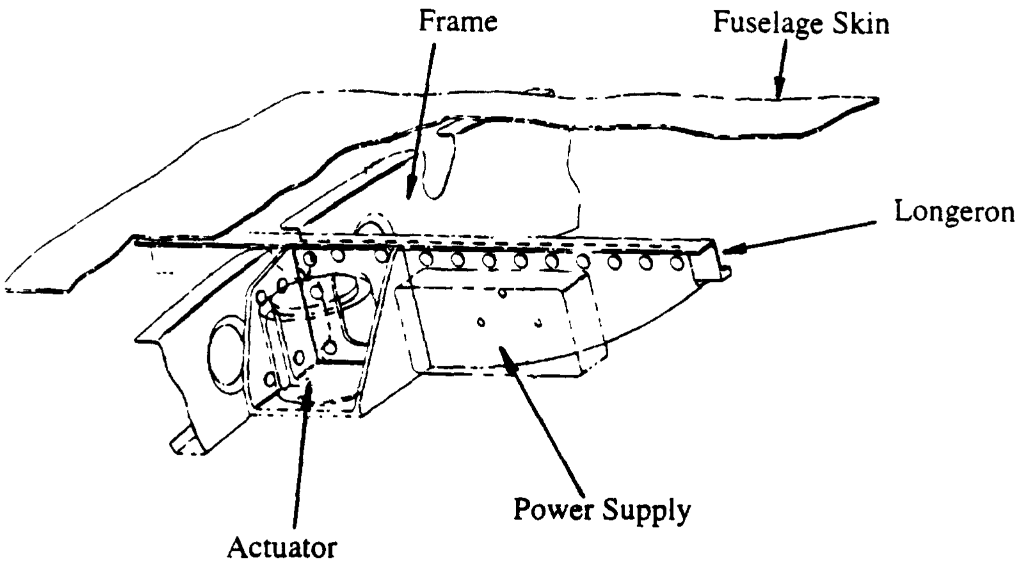


Figure 8. Inertial electromagnetic actuators used in the Dash-8 ASAC application [26].

Noise Reduction (dB)

	1 BF	2 BF	3 BPF	4 BPF
ASAC	10.5	7.6	4.4	3.0
ANC	8.0	6.6	3.6	0.4

Table 2. Averaged noise reductions using two active control approaches in a Dash-8 [26].

control systems are in use around the world today. A related ASAC system is being marketed by Lord Corporation in the U.S. [27]. The Lord system is similar except it has been applied as a production item to a Cessna Citation X, which is a turbo-fan engine aircraft. In this case the inertial actuators are located on the engine mounts (acting on the back) and error microphones are located in the cabin [27]. In this manner only the acoustically significant vibrations at the engine mounts are controlled which is similar to the ASAC principle. Very good global reduction of the turbo-fan N1 and N2 tones is achieved with this system. Both Refs. 26 and 27 used a feedforward LMS controller.

Quiet Power of the U.S. has successfully applied an ASAC system to reduce transformer radiated noise [28]. A diagram of the system is shown in Figure 9. The Quiet Power system consists of a combination of acoustic drivers and ceramic piezoelectric actuators bonded to the transformer casing as actuators while error microphones located in the radiated sound field are used. The acoustic drivers are used to control the 120Hz signal while the piezoelectric devices control the higher harmonics where the displacement requirements are less. The control approach is a MIMO feedforward LMS algorithm. Global reductions of the overall radiated sound field of the order of 12-15 dBA are achieved for a large power transformer. The significant frequencies are usually the fundamental (120Hz) and the first three harmonics (240, 360 and 480 Hz). The system has been applied to a number of operating transformer sites in the US and Canada.

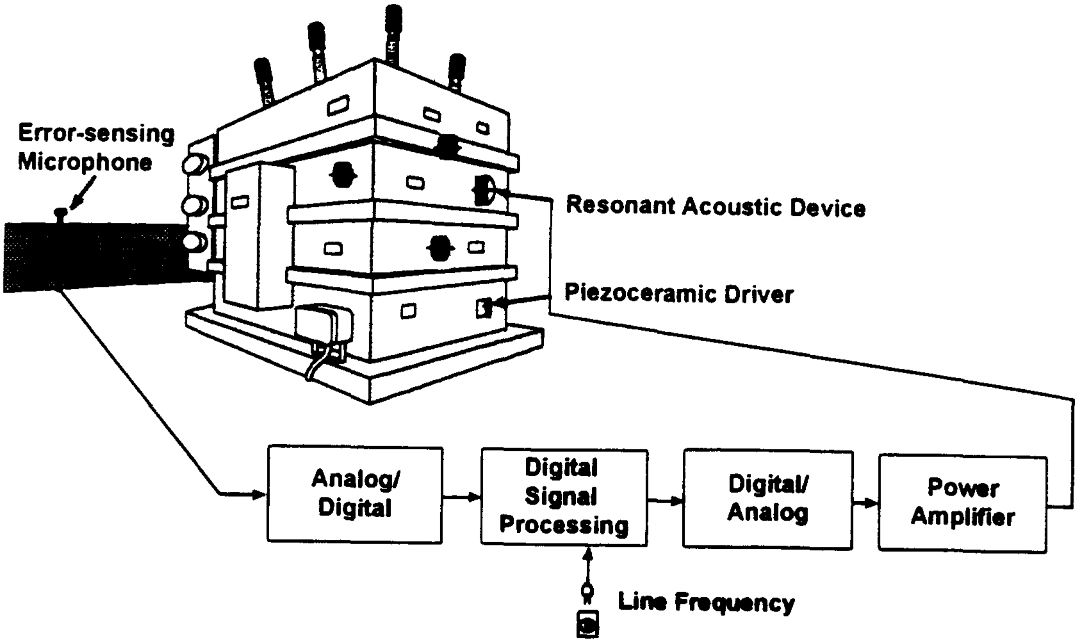


Figure 9. The Quiet Power ASAC System for reduction of power transformer noise [28].

Two areas which show much near term potential use of ASAC are in the reduction of train and automobile interior noise. Muller BBM in Germany [29] has recently demonstrated global reductions of train interior noise using electromagnetic actuators attached to the wheel bogies and error microphones in the cabin (reduction of the order of 7 dB were achieved). In related work, researchers at Catholic University Leuven in Belgium have shown that an ASAC system consisting of electromagnetic shakers attached to an automobile car chassis and used in conjunction with microphones in the car interior can provide significant global sound reduction [30]. If the cost effectiveness of these systems can be increased then it is likely they will be commercialized in the near future.

CONCLUSIONS

It can be seen that the field of ASAC is quickly expanding and starting to gain a technical maturity. The focus of the new research appears to be on actuators and sensors which can be integrated into the structure. The use of robust feedback MIMO controllers has recently appeared as well. Commercial systems based upon the ASAC technique are now starting to appear.

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