Active Noise and Vibration Control

Active Noise and Vibration Control

1. Objectives

Active Noise and Vibration Systems have the following objectives:

- To improve passenger comfort and crew effectiveness by reducing cabin and cockpit noise and vibration levels.
  Currently, pilot flying times are limited by exposure to noise and vibrations in turboprop and helicopter aircraft.
  Future workplace health and safety regulations will establish more rigid standards for exposure to cabin noise.
- To increase the performance characteristics of commercial and military aircraft by reducing vibration levels.
  Operational performance, manoeuvrability and fuel efficiencies are expected to increase with active vibration control of aircraft structures which are exposed to high levels of turbulence and buffet loads creating wing flutter, acoustic resonance in open bomb bays, rotor resonances and fuselage vibrations.
- To increase the lifetime of aircraft and improve component life cycle costs by decreasing fatigue loading which is produced by noise and vibration.

2. Background

2.1. Active Noise Control

Noise, as defined by the Webster's Dictionary, is "sound due to irregular vibration" or "any sound which causes discomfort to the hearer."

Sound is a constant fixture in our environment. The dynamic range of sound intensity the human ear can perceive is 10^7:1, this range is made more manageable through the use of a logarithmic scale which has the dB as its basic unit. A number of environmental sources are listed in the Table1. The human threshold of hearing on this scale is 0 dB.

Table 1. Common Sources of Noise

Noise Source	Sound Pressure (dB)
Threshold of Hearing	0
Whisper	20
Quiet Residential Neighbourhood	40
Normal Speech	60
Busy Office	80
Heavy City Traffic	100
Loud Music (or a Punch Press)	120
Air Raid Siren	140
Medium Jet Engine (Large Prop Aircraft)	160

The US Occupational Safety and Health Administration (OSHA) has determined that sustained sound levels greater than 90 dB can cause permanent damage. As a result the OSHA limits workers exposure to 90 dB sound levels to 8 hours per day. However, since the dB scale is logarithmic, the exposure duration for a 95 dB level noise should be limited to under 4 hours per day.

The importance of active noise control in the work place is becoming increasingly more important as a result of employee hearing loss resulting from long term exposure to workplace noise.

Industrial noise sources tend to have several distinct characteristics. One is turbulence or grinding, this is evenly distributed across the frequency bands and is referred to as "broadband noise". Another type of noise is "narrowband noise" which concentrates most of its acoustic energy at specific frequencies. When the noise is from equipment with rotary motions, a set of tones or "tonal noise" is produced. The sources for noise are numerous. For example, noise can radiated from engines, exhaust systems, fans, and blowers. Active noise control (ANC) was developed as a way to reduce if not eliminate some of these different types of noise.

ANC works on the basic principle of destructive interference, where the undesirable sound wave is countered with a sound wave of equal amplitude and 180 degrees out-of-phase with the undesirable sound. The result is that the sound waves cancel and the undesirable sound is eliminated. This principle is implemented in smart structures, including noise cancellation headsets, transformer quieting systems, and interior noise reduction in automobiles and aircraft.

ANC technology consists of sensors, signal conditioning, a control system, power amplifiers and actuators. In a typical ANC system operating in a steady harmonic noise field, the noise would be sensed with an array of microphones, the signals from which would be analyzed by a central processor unit/digital signal processor combination. This system may be configured differently depending on the acoustic objectives of the system which may be to minimize the power output of all acoustic sources, create a quiet zone around a single microphone, or use a loudspeaker as a sound absorber.

In order to meet these objectives, feedforward or feedback control strategies are often used. In the feedforward strategy, the noise is measured at the source or prior to reaching the area under control. This approach is used in a number of the quiet zone applications in aircraft and automobile cabins. In this strategy, an external noise source is measured at the source or in the primary sound field and electronically conditioned before creating the cancellation signal through a loudspeaker(s). This system often uses a second error microphone to measure the resulting sound field in the area being controlled.

Feedforward architectures are often used in applications involving the cancellation of noise in cavities, such as exhaust systems or passenger compartments. While, in the feedback strategy, the controller uses a high-gain negative feedback loop to drive the acoustic pressure at a microphone to zero. In this system no prior knowledge of the noise is necessary; however, the microphone and cancellation source need to be in close proximity to one another. This strategy is used effectively in the ANC headsets.

A number of different sensors and actuators are used in these applications. The sensors utilized in these smart ANVC systems include eddy current proximity sensors, tachometers (velocity sensors), accelerometers, microphones and piezoelectric sensors. For the most part, the use of proximity sensors and tachometers are used for determining the rotational characteristics of the noise source. Microphones are the most common sensors used in the monitoring of cavity noise. Finally, piezoelectric actuators are used to monitor the noise associated with panel vibrations such as those present in transformer structures.

The most common actuator used in the active control of sound is a relatively simple loudspeaker with a variable baffle. The loudspeakers are primarily involved in the cancellation of noise or sound waves by applying a "mirror image" sound wave to counter to the undesirable noise. By the superposition theory, the amplitudes of these waves cancel and a quiet zone is created. A second approach to active noise control involves cancellation of the noise at the source. In these applications, piezoelectric ceramics and electromagnetic shakers are popular, especially when used in the control of panel vibrations. These applications are considered to be examples of active noise control since the goal is to reduce the amount of auditory acoustic noise.

Over the last 5-10 years, the ability of digital controllers has increased to the point where complex control algorithms can analyze system's performances and adapt to system changes in real time in order to improve system efficiency. The majority of the active noise control applications use digital control or digital signal processing (DSP). For the most part the commercial applications of active noise control utilize a DSP board with a central processing unit (CPU). A CPU/DSP would use the signals and a model of the physical system, to produce inputs to the amplifiers which are used to drive a set of loudspeakers with the correct phase and amplitude so as to yield a zero net acoustic pressure.

Digital controllers utilize three main classes of control algorithms: power sensing, transform methods and waveform synthesis. In the power sensing algorithm, the acoustic power is detected and minimized. In the transform methods, the controlling parameters are in the form of a number of coefficients which are manipulated to minimize the noise. Finally, in waveform synthesis considerable information about the acoustic pressure field must be known, however, it is has the quickest adaptation time of the three methods (1/10 of the response time required by the other two methods).

Although the type of algorithms being used in research and development may vary, most active noise cancellation systems employ a variant of the least-mean-square algorithm (LMS), known as the filtered-x algorithm. This algorithm minimizes an error signal by manipulating a number of coefficients that are used by a digital filter. In such a system, the algorithm correlates an error signal (residual noise) with a reference signal (x) generated from a tachometer. The result is multiplied by an adaptation rate constant and used to adjust the relevant parameter of the adaptive filter. Ideally, this is done repeatedly for each filter parameter with the objective being a convergence that minimizes the error signal's average power.

In reality; however, the LMS algorithm does not converge due to the delay gain in the anti-noise signal's physical path. Using a compensating filter on the reference signal (filtered-x) restores the stability to the system. Typically, a control system of this type would require a DSP with the ability to operate at 10^6 operations per second, a low-pass filter (<500 Hz), an A/D converter and a D/A converter.

2.2. Active Vibration Control (AVC)

Vibration can cause damage or compromise precision instruments and/or human health, especially for operators of heavy equipment. Stray vibration may cause misreading and reduce sensitivity in navigational gyroscopes; in precision machining devices chatter vibrations present in a machine tool structure can severely reduce machining tolerances and mar surface finishes.

In the aerospace sector, vibration results in material fatigue, lower than optimal performance characteristics and limited pilot flying times. Elimination of vibrations may improve process accuracies, aircraft performance, pilot flying times and prevent damage. Undesirable vibrations can be attenuated using both passive or active damping techniques. Passive vibration control methods usually use techniques which increase the weight of the aircraft, such as the addition of isolating spring, dampers or material design. These passive techniques do not always provide sufficient bandwidth or attenuation to damp vibrations; while active methods which create nullifying disturbances are promising.

The basic principles of ANC can be applied to Active Vibration Control (AVC). In fact, the control hardware and control software architecture used in AVC systems are identical to those used in the ANC systems. For example, the AVC technologies incorporate sensors, signal conditioning, a control system, power amplifiers and actuators. In a typical AVC system vibrations are detected with an array of sensors, the signals from these sensors are analyzed by a central processor unit/digital signal processor combination and system actuators are activated accordingly using a analogue or digital control algorithm.

Typically the sensors used in the active shape control of a beam or panel include strain gauges, optical fibres, piezoelectric ceramics and piezoelectric polymers. For static displacements, the strain gauges tend to be more accurate than the piezoelectric sensors which operate better at higher frequencies. In the active members; however, a number of different sensors have been used, including eddy current displacement sensors, force sensors and piezoelectric velocity sensors and accelerometers.

The actuators utilized in active vibration control applications can either generate strain by utilizing bending or shear strains in panel structures or direct linear actuations in load-bearing members. The panel vibration damping applications include damping airframe vibrations in the fuselages of helicopters and propeller aircraft, aircraft wings, transformer enclosures and ducts. The structural member applications include the damping of vibrations in truss-type structures, active suspensions and active flutter suppression in wings. In addition to these applications, precision active members can also be used for structural shape modification. Although the actuators which generate shear can be very effective in reducing vibrations in panels and in other low-load applications, the majority of the load carrying applications are performed using active member-type assemblies. Moreover, in order for these systems to perform well, these actuators will be required to operate over a broad frequency bandwidth.

Piezoelectric actuators have higher bandwidth than are possible in shape memory alloys, they are more compact than magnetostrictive devices and they are bidirectional by nature, unlike electrostrictive materials which require an electrical bias in order to achieve the bidirectional capabilities. As a result, piezoelectric and electrostrictive devices are more popular in research and development activities. Although some research is being conducted into magnetostrictive materials by some research groups, the size limitations will prevent these materials to be used in active strut applications where the length of the strut is limited. However, in active suspension and active flutter suppression applications where large displacements are required, hydraulic and electromagnetic based actuators tend to be favoured in research and development activities.

As with the active noise control applications, the commercially available products tend to be based on DSP systems (Lotus active suspension) and proprietary control algorithms. A number of the experimental digital computers utilize SISO or MIMO controllers with customized control software. The majority of these customized programs are based on the Linear Quadratic Gaussian algorithm.

3. Importance

The development of Active Noise and Vibration Control (ANVC) technologies is driven by the regulatory bodies and competitive nature of commercial aerospace companies which require higher performance aircraft in order to maintain their market share. The importance of these systems are discussed in the following:

- Currently, the world research and development efforts focus on the reduction of cabin noise and vibration levels in regional aircraft. This is expected to increase passenger acceptance, leading to a larger market share while meeting the European workplace health and safety regulations.
- Active noise and vibration techniques are expected to reduce the noise and vibration levels while meeting the competitive need to produce light weight structures. Meeting this need will require innovative well engineered systems.
- The commercial airlines exert strong pressure to reduce life-cycle cost, including purchase cost and cost of maintenance. Aircraft which do not have a competitive balance of price, performance, durability and efficiency will rapidly lose market share.
- Military driven requirements for ANVC technology in helicopters, in fixed wing aircraft and high performance aircraft. In these applications control of vibrations in both primary and secondary structures can greatly increase the performance of these aircraft and lead to innovative new designs which were not implemented in the past due to problems associated with vibration.

4. Alternatives

The only alternative to active vibration control is passive vibration control. Noise and vibration control achieved by passive techniques in helicopters and propeller-driven fixed wing aircraft have much larger weight penalties than those associated with the active techniques. In addition, the bandwidth anticipated in ANVC technologies will surpass passive techniques. As a result, the added value expected from shape control and vibration control technologies is anticipated to have perhaps the most visible effect on aerospace designs in future aircraft.

5. Maturity and Risk

5.1. Maturity of Technology

Recently, active noise and vibration technologies have been applied to a number of prototype systems and are commercially available in certain niche markets. Active noise control systems which are commercially available or under development, include transformer quieting, cabin and cockpit quieting systems, fan and blower ducts, active headsets and active mufflers.

Active vibration control systems are also being developed for active engine mounts, active suspensions and flutter control. The following subsections will discuss particular examples in order to establish the current state-of-the-art in active noise and vibration control technologies in a number of sectors, including the aerospace sector.

5.1.1 Noise Cancellation Headsets (Commercial)

There are number of commercially available noise cancellation headsets available on the market through Bose, Sennheiser, Telex and NCT. These headsets reduce the low frequency noise levels, an area were passive methods have not been successful at attenuating noise. Low frequency noise in the workplace is known to cause hearing damage with long term exposures. These ANC headphones work on the same principles outlined above, the incoming noise is measured and processed to produce a 180 degree out-of-phase signal with the incoming noise.

An ANC industrial ANC headset made by QuietPower can reduce noise levels in the low frequency regime by as much as 20 dB in the 30 - 500 Hz range, while their safety and communications headsets have a broader bandwidth (30 - 1200 Hz) and reduce noise levels by 15 dB.

5.1.2. Active Muffler or Silencer (prototype)

An ANC active muffler (silencer) consisting of a cabinet mounted speaker at the end of the exhaust pipe, which outputs anti-noise in a ring around the end of the exhaust providing global cancellation of frequencies under 500 Hz. In this system, they used a microphone in the exhaust noise sound field to feedback the residual noise (after cancellation) so that the control algorithm (usually a LMS adaptive algorithm) can make the appropriate changes to reduce the microphone signal to zero.

By reducing the noise in the muffler, the whole system runs more efficiently by reducing the back pressure or flow resistance of the exhaust pipe.

5.1.3. Noise Reduction in Ducts (Commercial)

A specific application of ANC technologies involved reducing the noise levels from a 40 m high, 1.8 m diameter exhaust stack in an aluminium plant. The pure tone noise was being generated by two of the chimney's blowers. The single channel ANC systems were not applicable to the chimney, since high order acoustical modes were propagating in the chimney. As a result, a high mode ANC system was designed. For development a PVC tube was used to simulate the chimney, and appropriate frequencies were used to simulate the conditions at the plant.

The amplifier control was provided by a personal computer with a digital signal processing board which acts as the controller, which utilized a Multi-Input Multi-Output (MIMO) Filtered-X LMS algorithm. The sensor and actuator positions were then optimized using an error microphone that was in an error sensor's plane perpendicular to the cross section on the duct.

The results indicated that with five error sensors, the system was efficient up to 1300 Hz; while with 11 sensors, the system was efficient up to 2000 Hz. When the system was incorporated into the actual chimney, a 10 channel MIMO controller was utilized to reduce the noise levels by as much as 7-8 dB at 320 Hz. With additional tuning, the system is expected to reduce the noise levels by as much as 12-13 dB.

5.1.4. Vehicles (Developmental and Commercial)

Active noise control systems using interior loudspeakers to counteract low-frequency road noise have been effective in reducing road noise in the range of 100-200 Hz by as much as 7 dB. The system utilizes a number of accelerometers to detect the road induced vibrations and provide reference signals for a feedforward control strategy using a multiple error filtered-x least mean square (LMS) algorithm.

5.1.5. Turboprop Aircraft (Developmental)

Turboprop aircraft have high fuel efficiency than most fanjet aircraft due to their higher blade-tip speeds. However, the same design change that gave the turboprop the high fuel efficiency also increased the noise level in the interior of the plane.

In an effort to evaluate the implementation of active noise control, H.C. Lester and C.R. Fuller modelled a flexible cylinder which was excited by acoustic dipoles. The amplitudes of the internal monopole control sources were determined such that the area-weighted, mean-square acoustic pressure was minimized in the propeller plane. The results of the model predicted that there should be a 20 dB reduction in the interior noise levels. In a later study, piezoelectrics were used on a model aircraft fuselage to reduce the interior noise levels in a study by C.R. Fuller et al. The bimorph actuators were bonded directly to the structure and the error information was taken from up to two microphones located in the interior noise field. Global attenuation of 10-15 dB can be achieved using piezoelectric actuators, regardless of the nature of the vibration (structural or acoustic).

In an actual turboprop plane, the noise is generated by pressure pulses coming off the propellers and striking the skin of the aircraft. The airframe's skin vibrates and in turn generates low frequency noise at harmonics of the propeller blade rate (80 - 100 Hz). Active cabin noise quieting systems have been flown on several different aircraft and have been found to decrease the noise levels by as much as 10 dB.

In a more recent paper, a feedforward control algorithm using a rpm reference signal and a rotor position signal to reduce the far-field noise generated by a ducted propeller. In this paper, the feedforward waveform control algorithm was utilized in a test model. This system was effective at controlling the (1,0) and plane wave (0,0) modes of the propeller duct without increasing the sound pressure levels at other angular locations.

5.1.6. Transformers (Commercial)

The low frequency hum produced by large transformers can be reduced by applying active noise technologies. Once the frequency of the noise is determined, a signal of the same frequency but of opposite phase is used to attenuate the noise levels by as much as 16 dB (125 Hz). The problem with transformers is they can radiate in all directions and as a result an array of noise cancelling sources. Several of the power corporations are conducting research into the use of active panels for incorporation into substations. In these systems, piezoelectric transducer and sensors were mounted on the transformer tank and actively controlled to reduce the transformer noise by as much as 30 dB for the tonal noise levels and 10 - 20 dB for frequencies between 120 and 240 Hz.

5.1.7. Noise Reduction in Engines (Commercial)

Diesel engines waste approximately 0.7 %, for each 10" of water pressure drop, of its output energy overcoming the back pressure in the muffler system. Typically there is a 2 % recovery of energy with implementation of an active noise control system. Similarly, typical savings for an automobile engine would be 5 % (city) and 1 - 2 % (highway). Finally, industrial blowers could save as much as 20 % of the energy required to overcome the flow resistance in conventional muffling systems.

An ANC active gas compressor engine silencer reduces exhaust noise by as much as 8 dB, which corresponds to an 80 % decrease in emitted acoustical power. In this case the gas compressor engine consisted of a two cycle, 16"-bore and stroke developing 1040 hp at 320 rpm. The exhaust silencer was 16" OF and 29' long. A synchronous feedback noise cancellation technique utilizing a tachometer signal to provide noise rate information. Since the noise in this case are harmonics of the machines basic rotational rate, a digital signal processing (DSP) microcomputer can dedicate its resources to cancelling these frequencies. The cancelation algorithm is executed on a DSP computer that fits on a 250 cm^2 printed circuit board (1994).

The board consists of:

- A digital signal processing chip such as the AD2101 (10^6 operations/second)
- Two low-pass filters set at 500 Hz to avoid the confusion of high frequency signals with low frequency signals due to sampling
- An ANC an analog-to-digital (A/D) converter to measure the noise remaining after cancellation
- A digital-to-analog (D/A) converter to output the anti-noise
- The active silencer could globally cancel the majority of the low frequency noise below 27 Hz and reduce the tonal frequencies up to 200 Hz, which decreases the overall noise by as much as 8 dB.

A turbofan engine is also susceptible to tonal noise resulting from the rotational motion of the turbofan. In a system proposed and tested by Thomas et al., a multi-input-multi-output (MIMO) system was be used for the active control of the tonal noise of a fan in a turbofan engine. This active system using a three-channel (MIMO) system utilizing a feedforward filtered-x LMS algorithm implemented on a DSP board. In this experimental system, a reference sensor provides the noise signal, adaptive filters which drive the sound sources, error sensors in the acoustic far field of the engine and the control algorithm which adaptively controls the adaptive filter.

The system reduced the fundamental and the first tone by as much as 16 dB over a ±30 degree angle about the engine axis and a 15 and 5 dB reduction along the axis of the engine of the fundamental and first modes, respectively.

5.1.8. Precision Machining (Developmental and Commercial)

In precision machine tools, the reduction of vibrations during cutting operation has improved the control of these tools which is critical for precision operations. Chatter reduction during lathe cutting operations has been developed on the prototype level through the team effort of Giddings & Lewis, Pratt & Whitney and Kennametal, Inc. Similar research is being carried out by Michigan Technological University where a magnetostrictive actuator reduces the vibration of a cutting tool by utilizing an accelerometer and compensating control. AT&T and Kennametal have developed active control technology to halt the onset of chatter during cutting operations that use boring bars. McDonnell Douglas has also developed a five-axis, high-speed milling machine having reduced chatter and improved cutting performance.

5.1.9. Active Strut Member (Developmental)

The active member technologies are being developed to control the flexible motion of a precision truss structure. The key design criteria was developing a active member with appropriate stiffness and bandwidth. This device utilizes a piezoelectric stack that expands and contracts to change the length of the strut. The length of the strut is monitored by a sensor for precision control of the active member. These devices have a stroke length between 50 and 100 μm and a stiffness between 23,300 and 186,000 lb/in.

Using a positive position feedback (PPF) controller an active strut member was found to decrease vibration levels by as much as 35 dB after implementing the active control system. In a later paper by the same research group.

5.1.10. Active Suspension (Developmental and Commercial)

Lotus replaced a simple spring and damper mechanism with a DSP-controlled actuator. The DSP can sense as many as 16 inputs of load, displacement and acceleration of the vehicle and drives four hydraulically powered actuators. The most difficult challenge to Lotus is the development of the servo valves with a high enough power bandwidth for the hydraulic actuator to be able to actively damp road induced vibrations. The Lotus actuator has servo valves with 20 - 30 Hz switching capability, a 2 m/s linear velocity over a 100 mm stroke and 0-20 mA control-signal input. The active suspensions themselves require a closed-loop bandwidth from DC to 30 Hz to control the body resonances (approx. 1 Hz) and the wheel assembly resonances (10-15 Hz).

The Lotus active suspension control system has a cycle time of 1 msec, during which time the system samples 19 sensor inputs, computes new control data and delivers a drive signal to an output actuator coupling each wheel to the vehicle body. Each sensor input passes through a multiplexer to a 12-bit analog-to-digital converter (ADC) which takes 6 microseconds to digitize the analog signal. a static-RAM (SRAM) module sorts the output in the form of a set of digitized samples per system cycle. Signal conditioning circuitry precedes the multiplexer to provide gain and filtering, depending upon the type of sensor.

The Lotus DSP is based on the TMS320C30 μP with 8 kBytes each of RAM and 8 kbytes of EPROM. The subsystem uses the SRAM data set as input for its control algorithms. The processor outputs to four digital-to-analog converters which in turn feed four current-drive output amplifiers. The wheel actuators operate on a current drive range of±20 mA. The DSP uses an RS-232C channel which enables computer interfacing and a 1.4 Mbps port to enable data collection for analysis.

Toyota's piezo TEMS (Toyota Electronic Modulated Suspension) was been developed to improve the handling and stability of the automobile and the passenger's comfort. The TEMS is based on a road stability sensor and a shock adjuster. The road surface sensor consists of five-layers of piezoelectric mounted on the piston rod of the shock absorber. When a bump in the road is encountered, the sensor produces a voltage proportional to the resulting applied stress. This voltage is electronically monitored. The electronic control then supplies a signal to a 88-layer piezoelectric stack actuator which will counter the vibration produced by the encountered bump. The actuator stack can produce displacements as large as 50μm which is then hydraulically amplified up to 2 mm.

5.1.11. Airframe Vibration Control (Developmental)

Currently, the vibration problems associated with rotorcraft has been very active. The majority of this research focuses on helicopters. By reducing the vibration levels in helicopters; pilots can fly longer, the manoeuvrability of the helicopter is increased and the helicopter's fuel efficiency increases. There are a number of different methods of reducing the vibration being investigated. Prof. S. Hanagud and Dr. G.L.N. Babu of the Georgia Institute of Technology proposed to control airframe vibrations by placing piezoelectric sensors and actuators along the airframe to suppress vibrations at selected locations. The rotor/airframe was modelled using the airframe mass and stiffness in a finite element analysis for the airframe. Higher harmonic loading was also considered when modelling the rotor/airframe coupling.

In the model, the sensor senses the vibration and a voltage produced is a function of the piezoelectric sensor's properties and the type of flexural deformations which are occurring in the airframe. The sensor voltage signal is then measured by a controller and fed back to the actuator. From the model, the natural frequencies and associated eigenvectors have been calculated and a modal model was developed. Using H_∞ control theory, the sensitivity of the exciting force on the acceleration at the sensor. The authors then used a Glover-Doyle algorithm in a H_∞ controller with a 2.4" wide and 0.25" thick piezoelectric sensor and actuator pair. The simulated results showed a significant decrease in vibration. Recently, some of this theoretical research has been put into practice as Sikorsky Aircraft have been developing approaches to vibration induced problems in gear-meshing and helicopter rotors.

5.1.12. Flutter Control (Developmental)

Many different theoretical solutions for the suppression of airfoil flutter have been proposed by as many researchers, including the adaptive wing approaches described earlier. Another approach is to use the systems used in controlling the airfoil to counter the vibrations; however, this approach utilized sluggish hydraulic actuation. Still another approach is to damp the fluttering using acoustic excitation. In this case, acoustic waves are produced to counter the structural vibrations of the airfoil. In this system the vibrations of the airfoil are fed back to a controller and an appropriate sound wave is generated to cancel the airfoil vibrations. Recently, the use of piezoelectric actuators to prevent static and dynamic instability in a composite wing has been proposed by a number of authors. Both of these researchers modelled panel structures using different controlling schemes; however, in both cases they predict substantial increases in airfoil performance with piezoelectric based active vibration control.

6. Technological Risks

Effectiveness of ANVC is dependent on accurate modelling of the system which is being controlled. Errors in the initial modelling could lead to inefficiencies in the performance of the ANVC system. In addition, a number of reliability issues associated with ANVC still need to be addressed, such as fatigue lifetime and structural integrity. As a result, each potential aerospace application will have to be designed individually and the reliability issues associated with each design must also be treated independently.

These noise and vibration reduction goals must be achieved at minimal cost and weight penalty in the face of fierce international competition. In addition, the new AVC/ANC systems must not impose an undue maintenance burden on the operator.

7. Availability

Currently, all of the required component technologies necessary for successful implementation of ANVC are available: sensors, actuators and digital signal processing control systems.

A variety of suitable sensors are utilized in ANVC applications, including microphones, strain sensors, fibre optic sensors, velocity sensors, accelerometers and strain gauges. The design criteria for choosing point or distributed sensors for ANVC applications, include accuracy, bandwidth, reliable in the aerospace environment, weight and cost.

A number of actuators are utilized in ANVC applications, including: piezoelectric, magnetostrictive, shape memory alloy, electromagnetic and hydraulic actuators. The design criteria for choosing actuators for ANVC applications, include accuracy, bandwidth, displacement, load carrying capabilities, reliable, weight and cost.

Powerful DSP chips and general purpose CPUs are available for incorporation into ANVC systems. These components can incorporate complex algorithms for the fast data manipulation required in ANVC applications.

8. Breadth of Application

These technologies are of interest to fixed and rotary wing airframe manufacturers and to sensor/actuator and avionics suppliers. As discussed earlier, potential applications exist in the automotive, industrial and consumer sectors.

9. Cost-Benefit Analysis

The cost of the initial systems will include research and development of ANVC systems for specific applications. These costs will include modelling, design, performance and reliability testing and prototyping. The majority of the work will be to implement existing technologies into the an ANVC smart system which can easily and reliably interface with the existing aerospace control systems, including power, software and hardware specifications.

The benefits of this technology include:

- Longer flying times
- Better fuel efficiencies
- Large payload capabilities
- Longer distance travel (larger aircraft range)
- Increased passenger comfort

10. References

1. J.R. Gyorki, *Putting a Lid on Factory Noise*, Machine Design 106-112 March (1994)
2. J.N. Denenberg and J.M. Charry, *Energy Savings Through the Use of Active Noise Cancellation*, Guide to Energy Policy Act of 1992, Fairmont Press , Lilburn,GA (1992)
3. S.J. Elliot and P.A. Nelson, *Active Noise Control,* IEEE Signal Processing Magazine 12-35 Oct. (1993)
4. H.F. Olson and E.G. May, *Electronic Sound Absorber*, Journal of the Acoustical Society of America 25(6) 1130-1136 (1953)
5. T.J. Sutton, S.J. Elliott, A.M. McDonald and T.J. Saunders,*Active Control of Road Noise Inside Vehicles*, Noise Control Engineering Journal 42(2) 137-147 (1994)
6. J.N. Denenberg, S.K. Miller and M.A. Jay,*Active Compressor Engine Silencer Reduces Exhaust Noise*, Pipe Line Industry Jan. (1994)
7. J.C. Stevens and K.K. Ahuja, *Recent Advances in Active Noise Control,* AIAA Journal 26(7) 1058-1065 (1991)
8. L.J. Eriksson, M.C. Allie, C.D. Bremigan and J.A. Gilbert, *Active Noise Control on Systems with Time-Varying Sources and Parameters*, Sound and Vibration 16-21 July (1989)
9. L.J. Eriksson, *Computer-Aided Silencing - An Emerging Technology,* Sound and Vibration 42-45 July (1990)
10. M. Klasco and R. Baum, *Active Noise Cancellation Headphones: Principles and Products,* Sound & Communications 41(1) 44-54 (1995)
11. B. Kerridge, *Lotus Active Suspension Pushes the Racing Envelope*, EDN 50-53 Dec. 23 (1993)
12. S. Hanagud and G.L.N. Babu, *Smart Structures in the Control of Airframe Vibrations,* Journal of the American Helicopter Society 34 69-72 (1994)
13. A.C. Lee and S.T. Chen, *Collocated Sensor/Actuator Positioning and Feedback Design in the Control of Flexible Structure System,*Journal of Vibration and Acoustics 116 146-154 (1994)

14.P.P. Friedmann and T.A. Millott, *Vibration Reduction in Rotorcraft Using Active Control: A Comparison of Various Approaches,* Journal of Guidance, Control and Dynamics 18(4) 664-673 (1995)

15.P.-J. Lu and L.-J. Huang, *Flutter Suppression of Thin Airfoils Using Active Acoustic Excitations,* AIAA Journal 30(12) 2873-2881 (1992)

16.C. Nam and Y. Kim, *Optimal Design of Composite Lifting Surface for Flutter Suppression with Piezoelectric Actuators,*AIAA 33(10) 1897-1904 (1995)

17.R.C. Zhou, Z. Lai, D.Y. Xue, J.-K. Huang and C. Mei, *Suppression of Nonlinear Panel Flutter with Piezoelectric Actuators Using Finite Element Method*AIAA Journal 33(6) 1098-1105 (1995)

18.X.Y. Huang, *Active Control of Aerofoil Flutter,*AIAA Journal 25(8) 1126-1132 (1987)

19.D. Hrovat, *Applications of Optimal Control to Advanced Automotive Suspension Design,* Journal of Dynamic Systems, Measurement and Control 115 328-342 (1993)

This document or parts of it were contributed by Sensor Technology to the Smart Structures working group that developed the Technology Road Map for the Canadian Aircraft Design, Manufacturing And Repair and Overhaul.

Sensor Technology Ltd.

P.O. Box 97, 20 Stewart Rd.,
Collingwood, Ont., Canada
L9Y 3Z4
Telephone : (705) 444-1440
Fax : (705) 444-6787
Electronic mail : General information, requests for quotations, orders or catalogue requests: techsupport@sensortech.ca
Comments or questions about this site: webmaster@sensortech.ca.