Piezoceramic Applications for Product Vibration Control

Adam Bogue, **Brian D. Mulcahey** and **Ronald L. Spangler, Jr.**
Active Control eXperts, Inc., Cambridge, Massachusetts

The use of piezoceramic 'smart material' damping treatments to overcome problems with traditional passive damping systems is discussed. Active damping systems can be constructed by combining piezoceramic actuators and sensors with feedback control electronics.

Unwanted vibrations affect the performance, comfort and useful life of many products from vibrating baseball bats to noisy automobile interiors to fatigue destruction of aircraft parts. Traditionally, these unwanted vibrations are addressed with a variety of passive treatments including rubber mounts, foam and viscoelastic layers and friction and tuned-mass dampers. However, the performance of these solutions is inadequate for many products. In addition, temperature and geometry constraints sometimes make them impractical.

Often, problems with traditional dampers can be overcome or improved upon with piezoceramic 'smart material' dampers. Piezoceramics are highly efficient transducers which convert electrical energy into mechanical energy or conversely, mechanical energy into electrical energy. In most applications, piezoceramics are used as actuators or sensors. But these materials also can be used as vibration dampers. This is done passively (no added power) by shunting the electrical energy, converted from mechanical vibration energy, into a network that dissipates the energy into an electrical impedance.

Active damping systems can be constructed by combining piezoceramic actuators and sensors with feedback control electronics. Piezoceramic dampers outperform traditional dampers because of their high energy conversion efficiency, solid-state nature and relative temperature stability. Previously, the use of piezoceramics in vibration control applications has been limited for two reasons: device technology and research/education.

Basic research and theory into the mechanics of passive piezo damping is well documented.[1,2,3] In passive piezo damping applications, piezoelectric elements are attached on a vibrating structure in order to capture mechanical strain energy and convert it to electrical energy. The electrodes on the piezoelectric elements are shunted with an electrical impedance. The electrical impedance or shunt circuit dissipates the electrical energy as heat, providing the loss mechanism for increased structural damping. Figure 1 shows a schematic of a system for inducing damping in a structural mode by connecting a passive electrical network across the electrodes of a piezoceramic element bonded to a structure. Figure 2 shows the electrical schematic of the system.

There are two basic shunt circuit designs used in passive piezo dampers: the RC shunt circuit and the RLC shunt circuit. RC dampers provide moderate damping over a fairly broadband range (typically one decade of frequency) while RLC dampers provide much greater levels of damping over a much narrower frequency range. The choice of RC vs. RLC typically depends upon cost and the repeatability of boundary conditions (which determine the broad- vs. narrow-band nature of the disturbance).

Passive piezo damping offers distinct advantages over traditional passive damping technologies such as constrained-layer viscoelastics, foams and rubber materials. While traditional damping materials provide good performance for narrow operating temperature ranges, passive piezo dampers are comparatively unaffected by temperature and can perform under extreme conditions. Traditional damping materials cannot perform at low frequencies without adding significant mass. Piezo dampers can address broadband vibrations including low frequencies with minimal added mass.

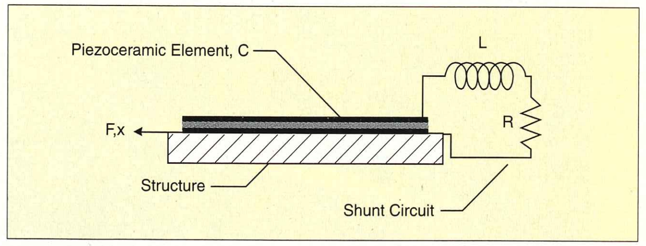


Figure 1. Schematic of electromechanical system for passive piezo damping.

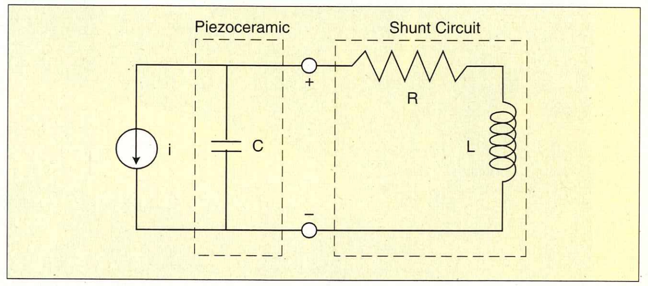


Figure 2. Schematic of electrical system for passive piezo damping.

Piezo dampers may also be highly tuned to target specific vibration modes or frequencies. In order to capture the most strain energy in a vibrating structure and thereby add the most damping, the passive piezo damper should attach to the structure in the area of highest strain for the vibration mode(s) of concern. Detailed structural modeling and modal analysis are required to optimize placement. For applications where modal density is high, a high-fidelity dynamic model of the structural system is necessary to insure that individual piezo dampers are located so that they do not bridge vibration node lines.

Piezo device technology historically has not made it easy for PZT (lead zirconate titanate) materials to be integrated into high-volume manufactured products. By their nature, PZT elements are fragile and require special handling during the product assembly process. PZT also requires electrical connections, commonly achieved through soldered wires that too, are fragile and require special handling. The other reason PZT applications have been limited is that basic research into piezoelectric properties is still in its infancy relative to other electromechanical coupling technologies. Furthermore, the knowledge-base of piezos within the general engineering community is limited. While electromagnetic theory and the application of solenoids and voice coils are common knowledge, piezos are not well understood by most product designers.

However, new device packaging and manufacturing techniques developed by ACX have solved these problems, enabling the use of piezoceramics in high-volume commercial vibration control applications. This QuickPack® technology insulates and strengthens piezoceramic elements while providing the means for incorporating electronic components in a package designed for mass-production. ACX has successfully applied QuickPack technology to develop a variety of innovative high-volume piezoelectric vibration control products.

Three such recently announced piezo-based dynamic control applications are discussed below: a passive damper for a baseball bat, an adaptive-passive damper for a mountain bike shock absorber and an active vibration control system for the F/A-18 fighter aircraft.

Smart Bat

Vibration has troubled baseball bat designers and users for years. Maximum hit-ball speed and minimum vibration occur at the bat's sweet spot (roughly 6 in. away from the hitting end). As the point of ball contact moves away from the sweet spot, hit-ball speed rapidly decreases while vibration increases. Increased structural damping can help to limit dynamic excitation in the bat, decreasing this painful 'sting.'

As with most sporting goods, user 'feel' is extremely important. Therefore, adding damping to a baseball bat without having a detrimental effect on feel becomes a difficult engineering challenge. For this reason, passive piezo damping which allows electrical tuning of damping characteristics is attractive for this application.

Figure 3 is a finite element model of the Smart Bat, showing normalized strain concentrations for modes 1 and 2 during a typical hit. Areas of highest positive strain are shown in red, while areas of highest negative strain are shown in pink. High strains – both positive and negative – are harmful and are targeted by the ACX damper.

Once optimal piezo damper location(s) have been found, the next step is to determine what type of piezoelectric material to use and how much is required. For most commercial applications, including the Smart Bat, a 'soft' piezoceramic such as PZT type-5 with a high transverse coupling constant k_{31} is most desirable. Using more piezo material will capture more strain energy, which provides high damping. As with all practical applications, performance and cost must be balanced. More piezo material provides greater damping, but it also translates to more weight and more cost.

The Smart Bat uses an RLC shunt circuit to maximize damping in modes 1 and 2. The shunt is a series of four inductors – two for each vibration mode to provide for omnidirectional performance. Figure 4 illustrates how the shunt circuit and piezoelectric elements are integrated into the handle of the bat.

As seen in Figure 5, the piezo damper reduces the vibration amplitude of the first mode by roughly 50% and the second mode by more than 70%.

Mountain Bike Smart Shock

Full suspension mountain bikes with front and rear shocks are designed to allow bikers to ride in off-road conditions. Shock and vibration characteristics vary with terrain and rider speed. In addition to causing rider discomfort, shock and vibration can cause the bike to lose contact with the ground, resulting in loss of control and maneuverability.

Traditional mountain bike shocks have a spring-loaded piston that compresses hydraulic fluid, forcing it through a bypass orifice. Traditional high-end mountain bike shocks have a screw that allows the rider to manually adjust the level of compression damping in the shock by increasing or decreasing the bypass orifice size. For example, if the rider expects to hit large rocks or roots, a hard shock is preferred.

Given that rider speed and terrain vary greatly during the course of a ride, variable performance is desirable. In many cases it is desirable to have variable compression damping forces even within a single compression cycle. For example, if the rider hits a large rock, the shock would ideally soften to absorb the impact force. However, if the shock remained soft through the full compression stroke, the shock would bottom out and transmit an impact to the rider. In this case, the shock would ideally become hard toward the end of the compression stroke so that it did not bottom out.

The Smart Shock, shown in Figure 6, uses a piezoceramic bending actuator located over the bypass orifice to control hydraulic fluid flow, thus adjusting the compression damping forces in the shock. As the actuator in a closed loop control system, the piezoceramic bending element adjusts the bike's suspension automatically and continuously, adjusting and optimizing performance for all riding conditions on the fly.

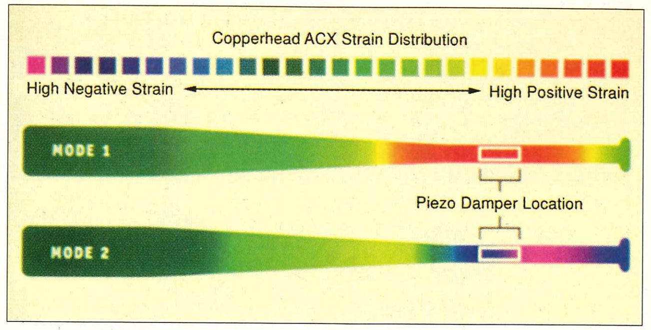


Figure 3. Copperhead ACX baseball bat strain distribution.

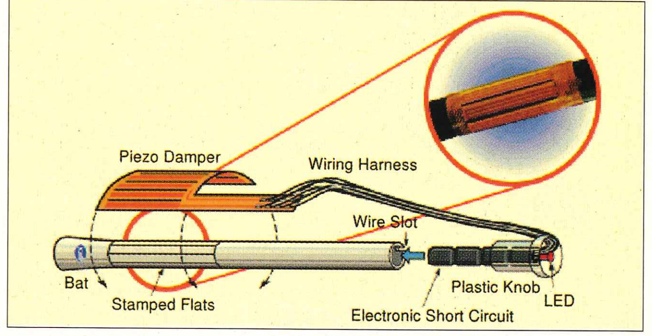


Figure 4. Exploded view of piezo baseball bat damper.

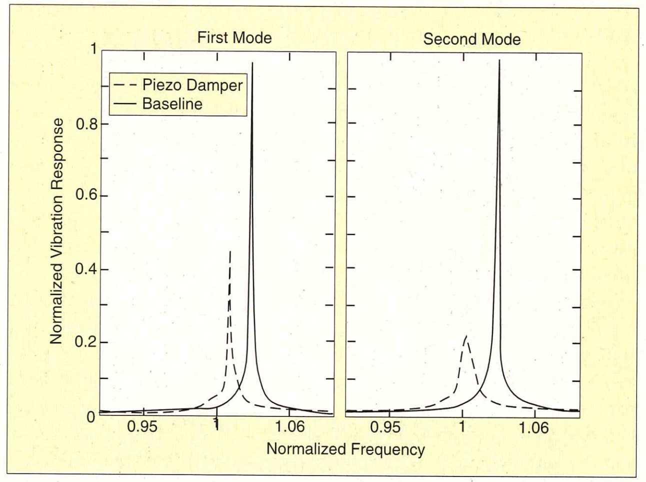


Figure 5. Baseball bat passive damper performance.

A sensor on the shock (using the giant magnetoresistive effect) reads piston speed and position, sending data to a microprocessor-controlled active feedback circuit. Based on an algorithm described in Figure 7, the circuit commands the piezo bending actuator in the valve. The actuator, in turn, regulates the flow of oil through the valve, which adjusts the shock damping. The result is a bike suspension that provides a smoother ride and increased tire-to-ground contact.

The principles of operation of a piezoelectric bending actuator are well documented.[4] Piezo bending actuators operate by having two independent piezo elements stacked on top of each other. Driving one element to extend while contracting the other causes the actuator to bend, creating an out-of-plane motion. Although many mechanical arrangements are possible, a bimorph actuator design typically has rectangular piezoceramic elements clamped firmly at one end, such as that shown in Figure 8. Force and stroke requirements for the application (e.g., for the Smart Shock, roughly 300 g blocked force and 100 mm free deflection) drive actuator design parameters including the length, width and thickness. For example, an

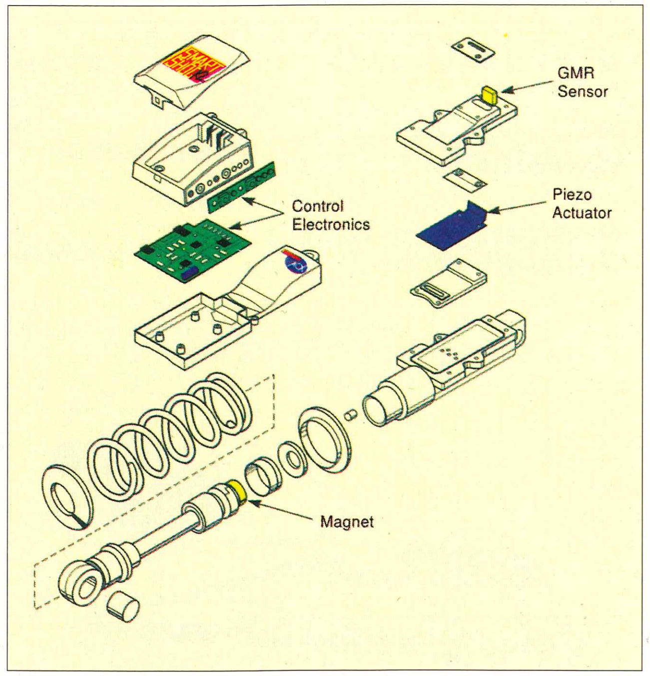


Figure 6. Components of the Smart Shock system.

increase in length increases stroke and decreases force. An increase in width increases force but has little effect on stroke. An increase in thickness increases force and decreases stroke.

An additional design consideration is bandwidth. Force and stroke are typically specified under quasi-static conditions, meaning that the actuator is operating well below its first resonant mode. If the application requires the actuator to operate at a higher frequency, then the dynamics of the actuator may affect its force and stroke output. For high bandwidth applications, the actuator is commonly designed so that the first resonant mode is 3× higher than the highest operating frequency for the application.

Along with actuator dimensions, another design variable for a piezoelectric bending actuator is piezoceramic material selection. For most commercial piezoelectric bending actuator applications, the goal is to minimize size while maximizing force and stroke for a given input voltage. As was the case with the passive piezo damping application, this leads to the use of a soft piezoceramic, such as PZT type-5 with a high piezoelectric constant, d_{31}. Other applications where power consumption or stability are more important may indicate a different material selection. Performance of the Smart Shock is shown in Figure 9.

Twin Tail Aircraft

Modern fighter aircraft are often required to fly at high speeds and high angles of attack. In this type of "Top Gun" operation, the extremely turbulent flow from the leading edge of the wings can impinge on the vertical tails of the aircraft, causing severe buffeting vibrations. This vibration increases the fatigue of critical structural members, thereby shortening the useful life of the tail assembly, which requires frequent inspections and reduces the aircraft's time on the flight line.

Recently, ACX has developed a piezoelectric active control system to combat the buffet problem in high-performance twin tail aircraft. This effort was carried out under a contract from the US Air Force, and in collaboration with the defense research organizations of the Canadian and Australian governments as well as NASA. CSA Engineering of Palo Alto, CA, and Boeing's Phantom Works in St. Louis, MO, were also team members. The heart of the buffet control system is a distribution of piezo strain actuators bonded to a typical twin tail aircraft structure. Other system components include vibration sensors which feed information to a DSP-based controller. The controller computes actuation commands, in real time, to mini-

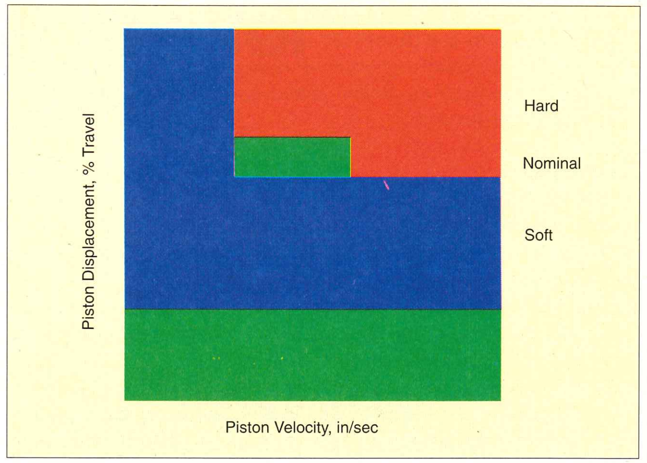


Figure 7. Smart Shock microprocessor control algorithm for smart mode during the compression stroke.

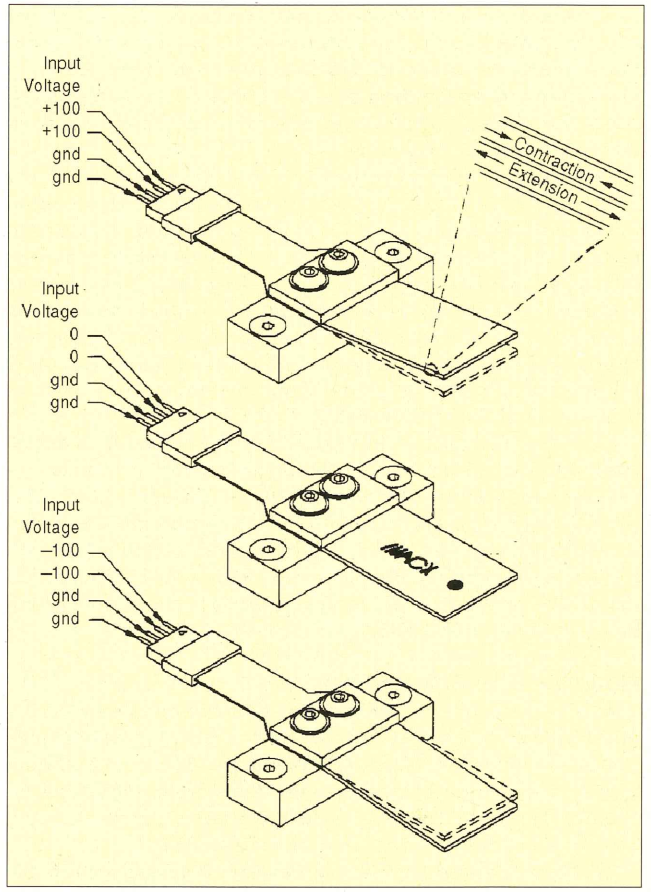


Figure 8. Piezoelectric bending actuator.

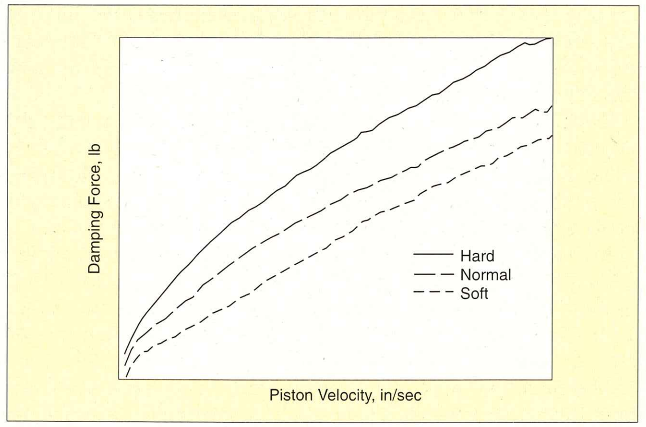


Figure 9. Smart Shock adaptive passive damper performance.

mize tail vibration. Those commands are fed to the actuators through high power amplifiers closing the active control loop. This system architecture is pictured in Figure 10.

The piezoelectric actuators, shown in Figure 11, were custom-designed for the aircraft's tail structure, based on ACX's patented QuickPack technology. The packaging, insulation and ease of electrical connection afforded by the QuickPack actuator are 'enabling technologies' for the use of piezoelectric control on military aircraft where specifications would not normally allow the use of high voltages required by raw piezoceramics. In fact, on operational aircraft it is likely that the actuators will be inside the tail skin, immersed in fuel.

Stringent weight and balance requirements for the aircraft limited the actuators to 20 lbs per tail. Using a finite element model (FEM) developed by CSA, ACX numerically optimized the thickness of the piezoelectric actuator distribution to maximize the controllability of the first (bending) and second (torsion) vibration modes of the tail. Canadian flight test data show that these modes at 15 Hz and 45 Hz, respectively, are the ones primarily excited by the buffeting disturbances from the wing. The resulting distribution was realized using one to three layers of 0.020 in. thick piezoceramic wafer per actuator location on each side of the tail.

An array of acceleration and strain sensors was designed, both to provide vibration signals for the feedback control and to monitor the performance of the control system during testing. In much the same way the actuators were distributed to maximize modal controllability, the sensors were placed to maximize the amount of information transmitted about the two modes of interest.

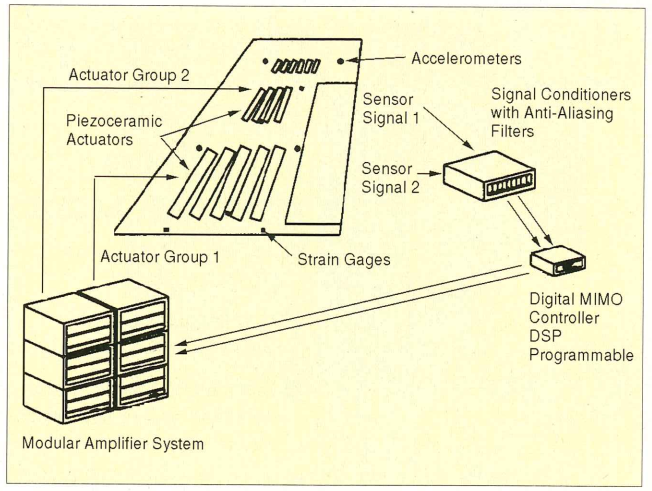


Figure 10. Piezo buffet load alleviation system architecture.

The two-input, two-output feedback control laws were designed using the common Linear Quadratic Gaussian (LQG) design technique. LQG produces optimal controls for minimizing a selected performance metric – in this case, the strain at the aft root attachment point of the tail to the airframe. The mathematical control laws were implemented using a real-time digital control computer, which updates the actuator commands 5000 times/sec.

All system components were fabricated at ACX and, as shown in Figure 12, integrated with an F/A-18 airframe in Australia at the International Follow-On Structural Test Program (IFOSTP) facility in Melbourne. IFOSTP is a program of the Australian Defence Science and Technology Organization (DSTO), chartered to study the life cycle fatigue of the F/A-18 tail empennage. The IFOSTP facility was specifically designed to simulate static and vibratory deformations through ground testing using electromagnetic shakers with 10,000 lb load capability. In the worst case buffeting condition, response of up to 100 g RMS is created at the tip of the tail.

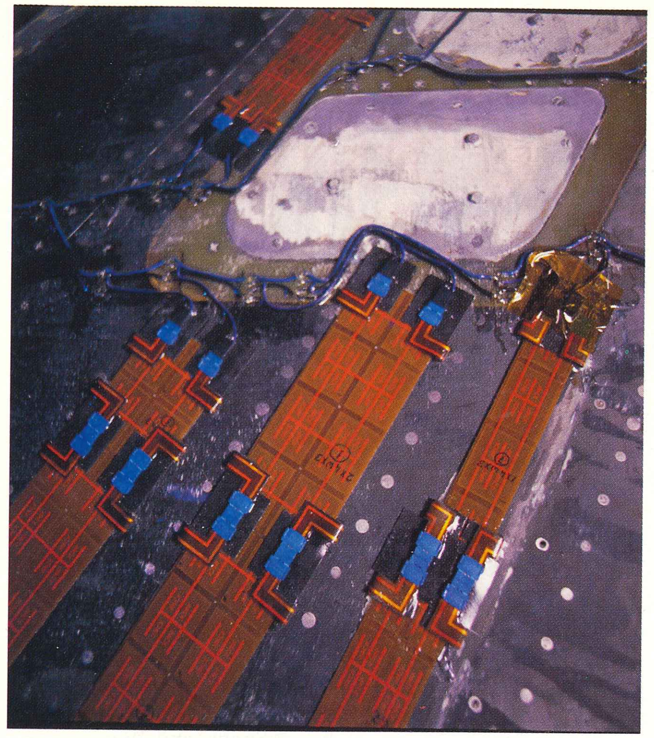


Figure 11. Close-up of ACX QuickPack piezo actuators. (Photo courtesy of AMRL.)

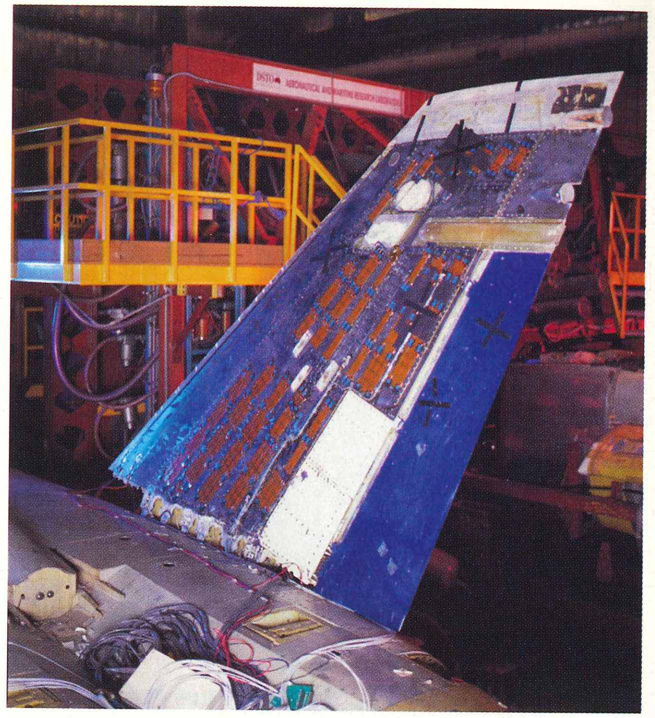
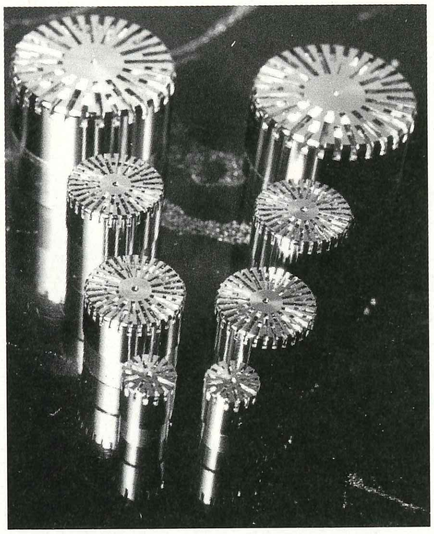


Figure 12. ACX custom-designed QuickPack actuators installed on one vertical tail surface of an F/A-18 airframe. The IFOSTP ground vibration test rig is seen in the background. (Photo courtesy of AMRL.)

The piezoelectric buffet control system was tested in two phases. In the first phase, ACX and CSA engineers gathered data on the open-loop (uncontrolled) system. The system models were updated to match the observed behavior, and control laws were designed to minimize vibrations within the limits of actuator forces. In the second phase of testing, these control laws were implemented and tested, under IFOSTP simulated flight loading. The closed loop testing demonstrated more than 50% reduction in RMS stress at the root of the tail structure, as shown in Figure 13.

Successful ground testing has paved the way for a number



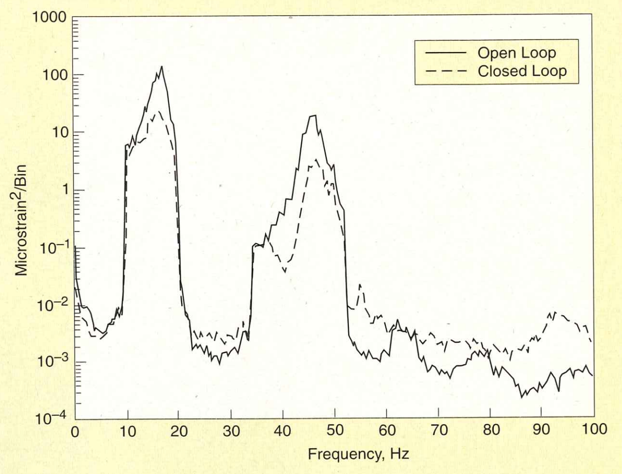


Figure 13. Open and closed loop spectral responses of aft root strain in the F/A-18 tail structure.

of possible future efforts, including scale-model wind tunnel tests at NASA's Langley Research Center and full scale flight tests in the US or Canada. With the advent of newer twin tail fighter aircraft like the F-22 Raptor, the need for active buffet load alleviation continues to grow.

Summary

Basic research into piezoelectric materials has opened up opportunities as this body of knowledge has been transferred to the product design and applications engineering community. As device manufacturers create packaging methods for delivering piezoelectric technology in a way that is manufacturable and cost-effective, new applications for piezoelectric materials will result. The Smart Bat, Smart Shock, and Twin Tail aircraft applications are several of the first of a new breed of applications where piezoelectric materials are used to improve everyday products. There are many products in the semiconductor, automotive, computer and white goods industries that could become applications for the use of piezoelectric materials in addition to sporting goods and aerospace applications.

References

1. A. R. Ramachandran, Q. C. Xu, L. E. Cross and R. E. Newnham "Passive Vibration Damping," Proceedings of the First Joint U.S./Japan Conference on Adaptive Structures, Nov. 13-15, 1990, Maui, Hawaii, B. Wada, J. L. Fanson and K. Miura eds., Technomic Publishing Co., Inc., Lancaster, PA, pp. 523-528.
2. R. Forward, "Electronic Damping of Vibrations in Optical Structures," *Journal of Applied Optics*, Vol. 18(2), pp. 690-697, 1979.
3. N. Hagood and A. von Flotow, "Damping of Structural Vibrations with Piezoelectric Materials and Passive Electrical Networks," *Journal of Sound and Vibration*, Vol. 146(2), pp. 243-268, 1991.
4. J. W. Waanders, *Piezoelectric Ceramics: Properties and Applications*, Eindhoven: Philips Components, pp. 26-40, 1991. SV