ABSTRACT

The paper reviews recent achievements in the application of smart-materials actuation to counteract aeroelastic and vibration effects in helicopters and fixed wing aircraft. A brief review of the induced-strain actuation principles and capabilities is done first. Attention is then focused on the smart rotor blade applications. Induced twist, active blade tip, and active blade flap are presented, with emphasis on experimental results. The fixed wing aircraft applications are considered next. Experiments of active flutter control, buffet suppression, gust load alleviation, and sonic fatigue reduction are discussed. Conclusions and directions for further work wrap up the paper.

1. INTRODUCTION

Aeroelastic and vibration control technology allows flight vehicles to operate outside the traditional flutter limitations, improves ride qualities, and minimizes vibration fatigue damage. Conventional active flutter and vibration control technology relies on the use of aerodynamic control surfaces operated by servo-hydraulic actuators as shown in Figure 1 (Giurgiutiu et al., 1995b). In this conventional configuration, the flutter and vibration suppression algorithms are implemented through the servo-valve/hydraulic actuator. Though widely used, conventional technologies for active control of flutter and vibrations have sever limitations, such as: (a) multiple energy conversions (mechanical, hydraulic, electrical); (b) large number of parts, i.e., potential failure sites; (c) high vulnerability of the hydraulic pipes network. Active-materials technology offers direct conversion of electrical energy to high-frequency linear motion. High-performance induced-strain actuators (piezo-electric, electro-strictive, or magneto-strictive) are capable of large forces and up to 0.1% strain (Figure 2a). This creates the opportunity for direct electrical-to-mechanical energy conversion. Electrical energy is easier to transmit throughout the aircraft, and electric lines are much less vulnerable than hydraulic pipes. The implementation of active-materials induced-strain actuation eliminates the need for hydraulic power systems, and relies directly on electrical-to-mechanical conversion (Figure 2b). In spite of large force and

Figure 1 Present-day configuration of aircraft hydraulic system: (a) system layout (b) details of the hydraulic actuator and servo-valve operation (Giurgiutiu et al., 1995b)

Figure 2 Active materials offer direct conversion of electrical energy in high frequency linear motion. However, their implementation into aircraft hydraulic system cannot be achieved without displacement amplification.
energy capabilities, active-materials induced-strain actuators (ISA) have very small strokes, limited by the inherent 0.1% cap on the induced strain response (Giurgiutiu et al., 1996, 1997b). For example, a 100-mm long actuator is capable of a mere 0.1-mm peak-to-peak stroke. Practical implementation of induced strain actuators into aircraft control system necessary must include displacement amplification mechanisms (Giurgiutiu et al., 1997a).

2. HELICOPTER APPLICATIONS

Helicopter applications of induced-strain actuation has received extensive attention (Giurgiutiu et al., 1994; Narkiewicz and Done, 1994; Chopra 1997). Conventional actuation solutions (hydraulics and electric motors) are impractical for on-blade actuation. Induced-strain appears as the only viable alternative. Two directions have been investigated: (a) distributed induced-strain actuation resulting in a continuous twisting of the blade; and (b) discrete actuation of a servo-aerodynamic control surface (flap, tab, blade-tip, etc.) to generate localized aerodynamic forces.

2.1 Induced Blade Twist

By distributing active material elements along the flight structure, a smooth continuous deformation is obtained. Since the active materials can be embedded in the structure, this solution has clear aerodynamic advantages over the discrete actuation concepts. A number of theoretical studies have been performed to estimate the degree of twist required to effect flutter and vibration reduction benefits (Nitzsche, and Breitbach, 1992a, 1992b; Nitzsche, 1993, 1994; Walz, and Chopra, 1994). These were followed by extensive experimental work, as shown next.

Induced Twist through PZT Wafers Embedded in Composite Blade Structure

Chen and Chopra (1997) describe the construction of a 1/8-Froude scale composite blade with diagonally oriented PZT wafers embedded in the fiberglass skin (Figure 3). Electrical activation of the PZT wafers induces twist of the blade. The blade was tested in Glenn L. Martin Wind Tunnel at the University of Maryland. Dynamic tests were performed in non-rotating and rotating conditions. Significant twist response was measured when excitation was close to resonance frequencies (50 Hz and 95 Hz). Maximum tip twist values at resonance frequencies were 0.35° and 1.1°, respectively. At non-resonance frequencies, the response was very small (Chen and Chopra, 1997).

Torque Plate Piezoelectric Actuator for Solid State Adaptive Rotors

Barrett (1993) build an electrically active torque plate consisting of a metallic substrate and diagonally attached PZT wafers. Twisting of the torque plate is created by activation of the PZT elements are with polarities on the top and bottom surfaces in opposing phase. A Solid State Adaptive Rotor (SSAR), consisting of the ISA torque plate attached to the root of a Froude scale composite blade, was constructed (Figure 4a). Activation of the torque plates produces produce pitch deflections of the blade. Bench tests showed a resonance peak at ~42 Hz, followed by the typical 3 dB tail drop (Barrett and Stutts, 1997). The twist amplitude measured at resonance was in excess of 10° (Figure 4b).
torque plate concept was applied to produce in-flight demonstration of a ISA control of model helicopter. A Kyosho Hyperfly helicopter model, featuring a Hiller servo-paddles control system was used. The complicated swash-plate assembly was stripped from the model helicopter and full control authority was turned over to a pair of ISA-activated Hiller servo-paddles (Figure 5a). Removal of the swash-plate assembly reduced the flight controls weight by 40%, the aircraft gross weight by 8%, and the parasite drag by 26% through appropriate fairing (Barrett, Frye, and Schliesman, 1998). Flight testing of the model was successfully performed (Figure 5b).

Figure 4  (a) Bench testing of a solid state induced strain actuated model helicopter rotor; (b) dynamic pitch amplitude of a solid-state model helicopter rotor under non-rotating conditions showing a resonance peak at ~42 Hz, followed by the typical 3 dB tail drop (Barrett and Stutts, 1997)

Figure 5 Model helicopter Gamara, equipped with piezoelectrically activated Hiller paddle: (a) bench tests; (b) flight demonstration; (c) schematic of the power and active control systems (Barrett, Frye, and Schliesman, 1998)
2.2 Active Fiber Composites for Rotor Blade Twist

Active fiber composites consist of a laminated structure of fiberglass plies and PZT-fiber plies. The PZT-fiber plies have continuous, aligned, PZT fibers in an epoxy layer, and polyimide/copper electrode films (Figure 6). The electrode films are etched into an inter-digitated pattern that effects electric field along the fiber direction, thus activating the primary $d_{33}$ piezoelectric effect (Rodgers and Hagood, 1998). Active fiber composite (AFC) were incorporated into the construction of a $1/6^{th}$ Mach scale CH-47D blade model (60.619-in span and 5.388-in chord) for wind tunnel testing at Boeing Helicopters, PA. Three diagonally placed active-fiber composite plies were incorporated in the co-cured D-spar blade lay-up. Activation of the diagonally placed fibers induces shear in the spar skin, which generates blade twist. A design goal of +/-2° blade twist was set. The blade specimen contained 7 groups of 6 AFC packs (3 in the top plies and 3 in the bottom) as shown in Figures 7. Of the 42 AFC packs installed in the blade, 11 were found to have poor electrical connection, and could not be activated. Thus, the blade actuation authority was somehow impaired. Bench tests performed at frequencies up to 67.5 Hz demonstrated a maximum twist authority of between 1 and 1.5° peak-to-peak (+/−0.5 – 0.75° amplitude). The full-length blade specimen was tested in a hover stand at 800 to 1336 rpm. The blade demonstrated hover testing resulted in recorded torsional strain and vertical hub force. At present, the active fiber technology is undergoing environmental stress evaluation (Morris, Pizzochero, and Hagood, 1999).

![Figure 6 Schematic representation of PZT-fiber composite illustrating the inter-digitated electrodes and the longitudinal expansion of the fibers (Rodgers and Hagood, 1998).](image)

![Figure 7 The full-length blade specimen: (a) schematic representation indicating the location of the 7 groups of AFC packs; (b) photograph of the test article indicating details of the electrical connections (Rodgers and Hagood, 1998a).](image)

2.3 Active Blade Tip with Bending-Torsion ISA Actuator

Bernhard and Chopra (1999) studied the smart active blade tip (SABT) concept for rotor blade vibrations and aeroelastic control (Figure 8). An all-movable blade tip is driven in rotational motion by an induced-strain rotary actuator placed inside the blade. It consists of span-wise segments of structural layers [+45°/0°/-45°] and diagonally placed directionally attached PZT wafer actuators. The actuator operates on the coupled bending-torsion principle. The span-wise segments are differentially energized such that, the induced-strain bending curvatures cancel out, while the induced-strain twist curvatures add up to create a net tip rotation. A model-scale bending-torsion actuator beam of 546 mm length, 25.4 mm width and 2 mm thickness was constructed and used for active blade tip and active blade twist experiments. Active

![Figure 8 The smart active blade tip (SABT) concept consists of all-movable blade tip driven by span-long actuator beam placed inside the blade (Bernhard and Chopra, 1999).](image)
blade tip experiments were performed with the bending-torsion ISA actuator incorporated into a 1/8 Froude scale blade for a 6-ft (1.83 m) bearingless rotor model. A 10% span smart active blade tip (SABT) was placed at the blade outer end. The blade tip response at 930 rpm varied between 2\(^{\text{nd}}\) and 2.50\(^{\text{th}}\) for 1, 2, 3, 4, and 5/rev excitation frequencies (Figure 9b). Active blade twist experiments were also performed with the bending torsion ISA actuator incorporated into a 1/8 scale Froude scale blade for a 6-ft (1.83 m) bearingless rotor model (Bernhard and Chopra, 1999). Activation of the bending-torsion actuator created twist of the blade. Hover tests at 875 rpm produced blade twist results from 0.30 at 1/rev through 0.50 at 5/rev excitation-frequencies.

![Figure 9](a) SBAT 1/8\(^{\text{th}}\) Froude scale model being tested in the University of Maryland hover stand; (b) tip deflection results at 930 rpm up to 2.50\(^{\text{th}}\) were recorded (Bernhard and Chopra, 1999).

### 2.4 Rotor Blade Flap Actuation

Servo-flap concepts have been investigated as a quicker-to-the-target approach to achieving induced-strain rotor blade actuation. Theoretical studies (Millott and Friedmann, 1994) highlighted the aerodynamic servo-flap concept benefits for active helicopter rotor control. The studies used an extensive aeroelastic model (including geometrical nonlinearities and advanced unsteady aerodynamic 2-D models) that was coupled with a vibration-reduction controller. Substantial vibration reductions were demonstrated at various helicopter airspeeds corresponding to advance ratios in the range \(\mu = 0.0 \text{ – } 0.4\). The required flap travel, hinge moment, and average power consumption were calculated.

#### 2.4.1 Bimorph Servo-Flap Actuation

Bimorph piezoelectric actuators (Figure 10) were used in early servo-flap experiments targeting the Boeing CH-47D tandem helicopter (Sprangler and Hall, 1989). A 1/5-scale stationary-model with a 10% chord flap was wind tunnel tested at various airspeeds between zero and 78 ft/sec, and at frequencies up to 100 Hz. Significant flap deflection, lift, and pitching moments were recorded, but the values were significantly below the theoretical predictions. An improved design using a multilayer ISA bender actuator, solid state flexural hinges, and impedance matching principles, was subsequently conceptualized, manufactured, and tested (Hall and Prechtl, 1994), with good bench test results (+/− 11° flap deflection over 0-90 Hz bandwidth). However, due to inherent limitations in the bimorph excitation concept (low mass efficiency and need for leading edge balance weights) this line of investigation was discontinued; attention was re-focused on ISA stacks (Prechtl and Hall, 1997).
Walz and Chopra (1994), and Koratkar and Chopra (1998) also used BIMORPH ISA rotor blade flaps. Initially, Walz and Chopra (1994) used trailing edge flaps of 20% chord, 12% span (0.85R - 0.97R) were built into a 36 in radius, 3 in chord composite blade model (Figure 11). Later, Koratkar and Chopra (1998) used a 4% span flap actuated by a 4-layer PZT bimorph actuator. A Hall sensor was incorporated into the blade to measure flap deflection during rotating blade testing. The testing was performed at various collective pitch values up to 4° collective pitch. Flap deflections of +/-8° were measured with a Hall sensor at the Froude scaled operating speed 900 rpm (Figure 12). Fulton and Ormiston (1998) also used bimorph flap actuation.

2.4.2 Piezostacks Actuated Servo-Flaps

Prechtl and Hall (1997) built a mechanically amplified ISA flap actuator (X-frame actuator) using a pair of EDO Corp. EC-98 PMN-PT piezo-ceramic stacks with 140 layers of 0.0221-in thick = 3.1-in (~80 mm) active length. In bench tests, the actuator showed 81 mil (~2.057 mm) free displacement, for frequencies up to 200 Hz, and a blocked force of 35.8-lb (~156 N), sustained under up to 69-g 135-Hz shaking (Hall and Prechtl, 1999). In a 1/6 Mach scale CH-47D rotor blade model, The X-frame actuator occupies the leading edge part of the airfoil (Figure 13). Mechanical linkages (control rod and reaction tube) are used to actuate the trailing edge flap horn and...
return the reactions into the actuator structure (Prechtl and Hall, 1998). In the scaled rotor blade model, deflection amplitude of almost $10^6$, sustained for increasing frequencies up to 150 Hz, was recorded (Figure 14). Lee and Chopra (1998) also reported using piezostacks for servo-flap actuation of scaled rotor blade.

![Figure 14 Deflection of the X-frame actuated trailing-edge flap in the 1/6 Mach scale CH-47D rotor blade model: (a) response for 3 Hz excitation at various voltage levels; (b) frequency response at maximum voltage excitation (Hall and Prechtl, 1999)](image)

2.4.3 Full-Scale Smart Rotor Blade Flap Experiments

A sustained program for full-scale implementation of smart materials actuation rotor technology (SMART) is under way at Boeing Mesa, Arizona. Straub (1993) analyzed the feasibility of using smart materials actuators for rotor blade control. Straub and Merkley (1995) presented a design study for the implementation of a smart rotor-blade flap on the AH-64 Apache helicopter. Full-scale proof-of-concept demonstration will be performed on the MD 900 bearingless rotor (Straub and King, 1996). The conceptual design calls for a trim tab for in-flight blade tracking and an active control flap for noise and vibration reduction, as shown in Figure 15 (Straub, Ealey, and Schetky, 1997).

![Figure 15 MD 900 helicopter and hingeless blade displaying the planned trim tab for in-flight tracking and active control flap for noise and vibration reduction (Straub and King, 1996).](image)

3. Fixed Wing Aircraft Applications

3.1 Flutter Suppression Studies

Heeg (1993) reported an analytical and experimental investigation of flutter suppression by piezoelectric actuators. The experimental studies were performed in Flutter Research and Experimental Device (FRED) at NASA Langley Research Center. FRED is an open-circuit tabletop wind tunnel with a 6-in x 6-in acrylic glass test section and 1500
in/sec maximum speed. The test article consisted of four components: a flexible mount system, a rigid wing, piezoelectric plate actuators, and a strain gauge bridge.

Figure 16 Flutter suppression experiments at NASA Langley Research Center: (a) Block diagram of closed loop control system for the induced-strain actuation flutter suppression experiment; (b) experimental results demonstrated a 20% increase in test article flutter speed from 580 in/sec to 697 in/sec (Heeg, 1993).

The test article was designed to a predicted plunge mode flutter condition at 560 in/sec. The flexible mount system had two plunge spring tines and one pitch spring. Two 1.5-in x 1-in piezoelectric wafer actuators were installed on one of the plunge spring tines near its root. The wafers were bonded to opposing sides of the plate to form a bimorph actuator. Strain feedback was acquired through a strain gauge bridge mounted on one of the spring tines. A PC digital control algorithm was implemented. The control signal was sent to a 25-times operational amplifier with a maximum voltage of +/-80 V (Figure 16). Experimental tests identified the open loop flutter at 580 in/sec. Closing the control loop increased the flutter speed to 697 in/sec, i.e., by 20%.

### 3.2 PARTI PROGRAM

The ability of induced-strain actuated adaptive wings to control dynamic aeroelastic phenomena was demonstrated through the Piezoelectric Aeroelastic Response Tailoring Investigation (PARTI). Wind tunnel tests in NASA Langley Transonic Dynamic Tunnel with a 4-ft long semi-span wing model successfully demonstrated flutter suppression and gust loads alleviation (McGowan, 1998). The wing model (Figure 17) consisted of a composite plate (graphite epoxy face sheets with aluminum honeycomb core) with 36 piezoelectric wafers surface bonded to each side of the plate. In addition, 14 resistance strain gauges and 4 accelerometers were used. The 36 piezoelectric wafers were arranged into 15 groups to be independently assigned actuator or sensor functions. Both active aeroelastic control and active/passive shunt damping were investigated. For active aeroelastic control, the power required to achieve effective control-law implementation was monitored. The maximum power consumption was found when the structure is perfectly controlled.

Figure 17 Piezoelectric Aeroelastic Response Tailoring Investigation (PARTI) scaled wing for wind-tunnel tests (McGowan et al., 1998)
This maximum power consumption was shown to be a function of material and geometric properties of the piezoelectric actuator and not to depend on the complex system dynamics. Studies were also performed to identify the optimal actuator activation configuration to minimize the power requirements. The tests proved that 12% increase in flutter dynamic pressure and 75% reduction of gust bending moment are achievable. Further investigations were focused on the use of passive/active shunts (Figure 18) connected to the piezoelectric wafers (McGowan, 1999). The active shunts utilize tuning methods to eliminate the most dangerous frequencies.

![Figure 18](image)

**Figure 18** Parallel shunt circuit for vibration control used in the PARTI project (McGowan et al., 1998)

3.3 ACROBAT Program

The feasibility of using active piezoelectric control to alleviate vertical tail buffeting was investigated under the Actively Controlled Response of Buffet Affected Tails (ACROBAT) program (McGowan, 1998). Tail buffet is a significant concern from fatigue and maintenance standpoints. Smart materials solutions to buffet problems were studied on 1/6-scale rigid full-span model of the F/A-18 aircraft tested in the Langley Transonic Dynamics Tunnel.

![Figure 19](image)

**Figure 19** ACROBAT program: (a) 1/6-scale rigid full-span wind-tunnel F/A-18 vertical tail model instrumented with piezoelectric actuators; (b) bending moment reduction through constant-gain active control (McGowan et al., 1998)

![Figure 20](image)

**Figure 20** (a) piezoelectric actuators bonded on the vertical tail (Hopkins et al., 1998); (b) power spectral density of acceleration measured on the vertical tail tip near the trailing edge on F/A-18 aircraft during ground tests (McGowan et al., 1998)
Piezoelectric wafer actuators were placed in opposing pairs on both surfaces of the vertical tail (Figure 19a). Constant-gain active control of the piezoelectric wafer actuators resulted in significant reduction of the root bending moment (Figure 19b).

3.4 Active Suppression of Tail Buffeting

A full-scale experimental program to investigate the active suppression of vertical tail buffeting vibrations in the F18 aircraft is currently under way in a joint US/Australia/Canada effort (McGowan, 1998; Hopkins et al. 1998). The full-scale test article is a the vertical tail on a no-longer flight-worthy fighter aircraft that is tested a the Aeronautical and Maritime Research Laboratory (AMRL) in Melbourne, Australia (Figure 20a). Preliminary ground test under simulated vibrations indicated that reduction of the peak bending moment response on the full-scale aircraft is feasible (Figure 20b).

Simpson and Schweiger (1998) conceptualized the use of piezoelectric damping for active suppression of buffeting vibration in the vertical tail of fighter aircraft. Manser et al. (1999) describe proof-of-concept experiments performed on a 2000-mm x 700-mm x 156-mm fin-box specimen performed at Daimler-Chrysler Aerospace in Germany. The fin box specimen was constructed from aluminum spars and carbon fiber composite skins of thickness varying from 14-mm at the root to 3-mm at the tip. The first natural frequency of the fin-box specimen was designed to correspond to that of a real aircraft (approx. 18 Hz). Custom-made piezoelectric wafer actuators with a voltage range of +/-200 V were applied to the carbon fiber composite skins (42 actuators in 4 groups per side).

Four custom-made high-power switching amplifiers of 2 kW rating (10 A at 200 V) over the 200 Hz bandwidth were employed. Modal response tests identified the first bending mode at 18.06 Hz with 0.44% critical damping. Open-loop tests proved that, at the first bending resonance, a maximum tip response of 13.4 mm could be attained. Closed loop tests were performed with an variable-gain analogue feedback amplifier (Figure 21). The closed-loop tests demonstrated critical damping increase from 0.44% to 3.70% as the feedback gain was varied from 0 to 20 (Figure 22).

3.5 Active Suppression of Skin Panel Vibration

Acoustically induced skin panel vibrations due to engine noise and flow turbulence can lead to early fatigue failures and are a major maintenance concern. Larson et al. (1998) describe the use of piezoceramic wafer actuators for active vibrations suppression of an acoustically excited B-1B aircraft skin panel. A 24-in by 10-in highly curved 0.080-in thick panel on the TDS B-1B test bed aircraft was instrumented with PZT wafer actuators, 14 for symmetric actuation, and 8 for anti-symmetric actuation. Each actuator has a 1-in by 1/3-in area. The control laws were processed on a Motorola 68040 microprocessor chip. The target of the active control experiment was to stabilize the modes below 1500 Hz and control the modes in the range 400 – 800 Hz. The system successfully reduced the fundamental panel-vibration modes by 79%, for the takeoff conditions, and about 46%, for transonic flight conditions. The higher modes were reduced by 25%.
4. CONCLUSIONS

Smart-materials induced-strain actuation (ISA) for aeroelastic and vibration control have evolved from laboratory scale proof-of-concept demonstrations to full-scale helicopter and airplane implementation. So far, the research efforts have channeled on two approaches: (a) distribute/continuous induced-strain actuation with embedded/distributed active materials; (b) discrete/pointwise excitation using active-material based actuators. Distributed induced-strain actuation has come at odds with the high inherent stiffness of traditionally designed structures. Consequently, experimental results, e.g., induced-strain twists, have not been very impressive. To achieve better results, a multidisciplinary optimization approach, including ISA effects, needs to be taken (Wilkie, Belvin, and Park, 1998; Schweiger, 1999). Discrete actuation has been more successful, partly due to the separation of variables, and partly because it lends itself easily to retrofitting existing structures. In discrete actuation, the major challenge is to amplify the patently small active-material ISA response in order to create usable actuator stroke output. A number of ingenious solutions have been developed, especially for helicopter applications (Figure 23).

The upcoming challenges will be connected with the system integration of the smart materials devices into the overall weight and power balance of the aircraft. Significant power supply, airworthiness, and reliability problems are expected. Among them, two are more acute: (a) the development of compact on-board power amplifiers capable of handling the large reactive power requirement of the piezoelectric system; and (b) the utilization of the full frequency bandwidth capability of the piezoelectric devices through frequency devolution and peak energy per cycle magnification.

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6. REFERENCES
