MECHATRONICS ASPECTS OF SMART MATERIALS INDUCED STRAIN ACTUATION

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Abstract: The mechatronics aspects of smart materials induced-strain actuation are investigated. Smart materials, a.k.a. active materials, are able to transform electric, magnetic, thermal, or other energy fields into mechanical deformation, i.e., strain. These physical properties have made smart materials ideal candidates for smart structures actuation, in situations where conventional actuation is impractical, or inappropriate. Though the energy and power densities of active materials per se are impressive, the utilization of active-materials based actuation devices is still very limited. The reason for this situation is discussed from the viewpoint of overall system performance, that includes not only the active material, its casing and prestress mechanisms, but also the power supplies and electronics that are integral part of its operation.

1. INTRODUCTION

Smart materials, a.k.a. active materials, are able to transform electric, magnetic, thermal, or other energy fields into mechanical deformation, i.e., strain. These physical properties have made smart materials ideal candidates for smart structures actuation, in situations where conventional actuation is impractical, or inappropriate. The harsh high-g environment at the tip of a rotating helicopter blade (> 500 g acceleration) is impractical for conventional electric motors or hydraulic power. The distributed actuation applied on a thin-wall space structure by an array of wafer size piezo-actuators cannot be matched by conventional actuators in terms of distributivity and energy density. Direct electrical displacement/strain control is another factor that makes induced-strain actuators ideal candidates for vibration suppression applications. In spite of their obvious benefits, practical use of smart material actuators is still restricted to laboratory examples and proof-of-concept demonstrators. Though the energy and power densities of active materials per se are impressive, the utilization of active-material actuation devices is still very limited. One reason for this situation is that design of active material actuation solutions is not yet done from the overall system performance viewpoint, i.e., including not only the active material, its casing and prestress mechanisms, but also the power supplies and electronics that are integral part of its operation.

1.1 State of the Art in Aerospace Induced-Strain Actuation

Aerospace adaptive control through induced-strain actuation has been intensively researched in recent years. With the advent of high-performance electro-active and magneto-active materials and actuators at accessible prices (Giurgiutiu *et al.*, 1994), the road has been opened for revolutionary changes in the aircraft flight control systems design and construction. Active materials technology allows the transition from conventional mechanical and/or hydraulic flight control systems to all electric concepts in which the control power and energy are transmitted across the aircraft in electrical form and are transformed into mechanical action at the control surface location. In this concept, vulnerable hydraulic lines are being replaced by the much more robust electric conductors, while a large number of hydraulic paraphernalia (accumulators, cocks, valves, tanks, etc.) might simply disappear. The implementation of induced-strain actuating concepts for adaptive flight control, is currently pursued on two parallel paths:

1. Deformable aerodynamic surfaces (wings, tailplanes, rotor blades, etc.) activated by embedded induced strain active-material fibers (Ehlers and Weisshaar, 1990; Lacers *et al.*, 1990; Song *et al.*, 1993, Chen & Chopra, 1993, etc.).
2. Rigid control surface (ailerons, flaps, leading edge flaps, etc.) with induced-strain active-material actuators replacing the conventional hydraulic cylinders or electric motors (Dadone, 1995; Straub, 1995; Kudva, 1995).

The first direction aims at creating a deformable aerodynamic surface similar to that met in the animal world. This concept is, undoubtedly, visionary and full of attractive benefits for adaptive control and for performance and maneuverability improvement, since it allows the simultaneous use of span-wise and chord-wise control algorithms. However, the implementation of the deformable aerodynamic surface concept is not straight forward, and has encountered considerable difficulties. The building blocks of a deformable adaptive aerodynamic surface need to be first developed and individually certified. The aircraft structural design philosophy must be revised and updated to incorporate the concept of highly deformable aerodynamic surfaces.

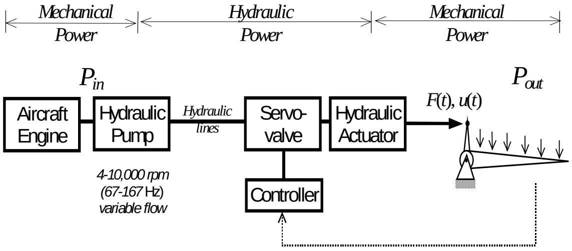

Figure 1 Schematic representation of a conventional flight control system.

The second direction aims at modifying existing flight control concepts by replacing the traditional actuation methods with lighter, less complex, more responsive, and more reliable induced-strain actuators. This concept retains the limitations of rigid and localized control surfaces, but its implementation is easier since it utilizes, to a large extent, existing techniques (Giurgiutiu *et al.*, 1995a). It offers a gradual approach to the implementation of induced-strain actuation principles, and its experimentation will provide practical experience into the specific behavior and limitations of induced-strain actuators (Giurgiutiu *et al.*, 1995b). In this paper, our focus will be induced-strain adaptive control using a conventional control surface and an induced strain actuator prime mover.

1.2 Conventional Flight Control Systems

Conventional flight control systems based on hydraulic operation with servo-valve control have also been used for adaptive control by superposing a controller signal onto the servo-valve electrical input. Figure 1 presents a simplified representation of a conventional flight control system. The power uptake from the aircraft engine is used to drive a variable-flow axial-pistons hydraulic pump. The hydraulic pump delivers constant-pressure hydraulic fluid to the various consumers inside the aircraft. The flight control system uses electro-hydraulic servo-valves (Figure 2) to modulate the flow of fluid to the hydraulic actuator. The electro-hydraulic servo-valve directs the constant-pressure hydraulic supply into the advance and retreat chambers of the hydraulic actuator.

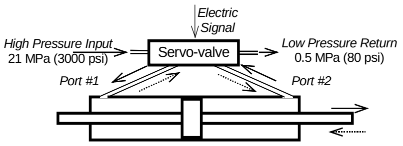

Figure 2 Schematic operation of a hydraulic actuator under servo-valve control.

To make the piston advance (full arrows), the servo-valve directs hydraulic pressure to Port #1, while connecting Port #2 to the low pressure return circuit. To achieve retreat (dashed arrows), Port #2 is pressurized, while Port #1 is connected to the return circuit. Thus, a sinusoidal electrical signal sent by the controller to the servo-valve is eventually transformed into a sinusoidal motion of the hydraulic actuator. The output rod of the hydraulic actuator is connected to the hinge-arm of the flight control surface (Figure 3), and puts it into oscillatory motion.

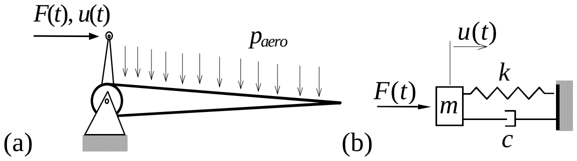

Figure 3 Schematic representation of a mechanical system: (a) aerodynamic control surface; (b) mass-spring-damper model

The performance limitations of hydraulic flight control systems lie in their poor high frequency response. The hydraulic-flow switching capabilities of the servo-valves are limited. To achieve high output, a two or three stage cascade can be used in the servo-valve construction, but this increases its complexity, weight, and overall dimensions. Another limiting factor is the capability of the hydraulic system supply. To accommodate high flow rates, large supply pipes must used, which creates obvious weight and space problems. For these reasons, the frequency bandwidth of hydraulic flight controls is somehow limited.

1.3 Mechanical Power and Energy for Active Vibration Control

Figure 3a shows an aerodynamic control surface, while Figure 3b presents the equivalent mass-spring-damper system. The parameters *m*, *k* and *c* represent the effective mass, stiffness, and damping as seen at the hinge-arm connection. These quantities include mass inertia of the control surface, mechanical friction effects, and the non-stationary aerodynamics effects such as aerodynamic mass, stiffness and damping. For harmonic motion, $u(t) = \hat{u} \sin \omega t$, the force is

$$F(t) = \hat{F} \sin(\omega t + \psi) , \qquad (1)$$

$$\hat{F} = \hat{u}\sqrt{(k-\omega^2 m)^2 + (\omega c)^2}\ ,\ \psi = \tan^{-1}\tfrac{c\omega}{k-\omega^2 m}\ .$$

Power management evaluations of a conventional flight control system usually relies on the assumption that no useful power can be recovered through the low pressure return circuit. Even with the hydraulic actuator acting against a spring (pure reactive power), none of the power needed to move the piston forward will be recovered during the piston retreat. This assumption is justified by the large difference between the pressure in the high-pressure line (typically 21 MPa or 3000 psi) and that in the in the low-pressure line (typically 0.2-0.5 MPa or 30-80 psi). Under this assumption, the mechanical power output from a hydraulic actuator acting against the spring-mass-damper system shown in Figure 1 needs to equal the sum of the active and reactive mechanical power amplitudes, i.e.

$$\begin{aligned} P_{out} &= P_{active}^{mechanical} + \hat{P}_{reactive}^{mechanical} \\ &= \omega\tfrac{1}{2}\omega c\hat{u}^2 + \omega\tfrac{1}{2}\sqrt{(k-\omega^2 m)+(\omega c)^2}\,\hat{u}^2 \end{aligned} \tag{2}$$

For systems with low damping, acting off-resonance, the reactive power is dominant, and Equation (2) takes the simpler form

$$P_{out} \approx \omega\tfrac{1}{2}\hat{F}\hat{u} = \omega\tfrac{1}{2}\sqrt{(k-\omega^2 m)+(\omega c)^2}\,\hat{u}^2 \tag{3}$$

Under quasi-static conditions, the inertia and damping terms of the aerodynamic forces can be ignored, and Equation (3) simplifies even further by taking $\hat{F}$ equal to the static aerodynamic control force. The power input to the conventional flight control system, P_{in}, equals the output power plus losses:

$$P_{in} = P_{out} + P_{loss} \tag{4}$$

The power losses, P_{loss}, of a hydraulic flight control system can be traced to:

- inefficiency of the hydraulic pump;
- viscous friction of the hydraulic fluid flow through the supply lines;
- internal friction of the hydraulic actuator.

1.4 Active-Materials Induced Strain Actuation

Active materials exhibit induced-strain under the action of an electric or magnetic field (Chopra, 1996). Most common active materials are:

a) PZT - Lead Zirconate Titanate –a ferroelectric ceramic material with piezoelectric properties and reciprocal behavior that converts electrical energy into mechanical energy and vice-versa. PZT-5 is one of the most widely used formulations for actuator applications. The behavior of the PZT material is quasi-linear, though hysteretic. Reversed polarity can be accommodated in moderate quantities (25-30%).

b) PMN - Lead Magnesium Niobate — An electrostrictive ceramic material with piezoelectric properties. PMN does not accept reverse polarity, but has much less hysteresis.

c) TERFENOL - TER (Terbium) FE (Iron) NOL (Naval Ordinance Laboratory) — a magnetostrictive alloy consisting primarily of Terbium, Dysprosium, and Iron. In practice, TERFENOL materials are made to exhibit quasi-linear piezomagnetic behavior through the application of bias fields.

The modeling of active materials behavior is achieved, in the first approximation, through the general constitutive equations of linear piezoelectricity (ANSI/IEEE Standard 176-1987). These linear equations describe a tensorial relation between mechanical and electrical variables (mechanical strain S_{ij}, mechanical stress T_{ij}, electrical field E_i, and electrical displacement D_i in the form:

$$\begin{aligned} S_{ij} &= s_{ijkl}^{E} T_{kl} + d_{kij} E_k \\ D_j &= d_{jkl} T_{kl} + \varepsilon_{jk}^{T} E_k\ , \end{aligned} \tag{5}$$

where s_{ijkl}^{E} is the mechanical compliance of the material measured at zero electric field (E = 0), ε_{jk}^{T} is the dielectric permittivity measured at zero mechanical stress (T = 0), and d_{kij} is the piezoelectric coupling between the electrical and mechanical variables. For magneto-active materials, a set of equations similar to Equations (5) can also be derived:

$$\begin{aligned} S_{ij} &= s_{ijkl}^{E} T_{kl} + d_{kij} H_k \\ D_j &= d_{jkl} T_{kl} + \mu_{jk}^{T} H_k \end{aligned} \tag{6}$$

where, H_k is the magnetic field intensity, and μ_{jk}^{T} is the magnetic permeability under constant stress. The coefficients d_{kij} are now defined in terms of magnetic units. The magnetic field intensity H in a rod of length L is related to the current in the surrounding coil (with n turns per unit length) through the expression:

$$H = nI \tag{7}$$

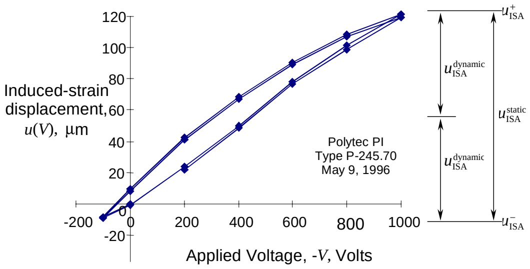

Figure 4 Typical displacement vs. voltage characteristics of a commercially available induced-strain actuator.

1.5 Power, Energy, and Efficiency of Active-Materials Induced-Strain Actuation

The power, energy, and efficiency of active-materials induced-strain actuation depend on two major factors: (a) active-material intrinsic properties; and (b) design characteristics of the active materials embedment and displacement amplification scheme. Giurgiutiu *et al.* (1996, 1997b) studied the intrinsic properties of commercially available active-material transducers. Full stroke conditions were considered, and a secant linearization approach was adopted. The maximum energy output from the induced-strain actuator was calculated for the matched stiffness conditions, i.e., when the internal stiffness of the actuator equals the stiffness of the external application. Typical energy density values found in these studies were placed in the range, 2.71-15.05 J/dm^3 (0.292-1.929 J/kg) under static conditions, and 0.68-3.76 J/dm^3, (0.073-0.482 J/kg) under dynamic conditions. Power densities of up to 23.6 kW/dm^3 (3.0 kW/kg) were predicted at 1 kHz. The overall efficiency of active-material actuation depends, to a great extend, on the efficiency of the entire system that includes not only the active-material transducer, but also the displacement amplification and the power supply.

1.6 Induced-Strain Actuated Flight Control Systems

Commercially available high-performance induced-strain actuators (piezo-electric, electro-strictive, or magneto-strictive) are capable of large forces and up to 0.1% strain (Figure 6). Induced-strain actuators create 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. In spite of their large force and 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 must include displacement amplification mechanisms (Giurgiutiu *et al.*, 1997a).

The implementation of active-materials induced-strain actuation eliminates the need for hydraulic power systems, and relies directly on electrical-to-mechanical conversion. Figure 7 shows a simplified representation of a induced-strain actuated flight control system using electro-active materials. The power uptake from the aircraft engine is used to drive the electric generator which delivers 115 V @ 400 Hz electric power to the various consumers inside the aircraft. The solid-state induced-strain actuation of the flight control surface consists of a high-voltage power amplifier and the electro-active material coupled to a displacement amplification device. The high-voltage power amplifier follows the controller demands and uses the 115 V 400 Hz electric power supply to create the power signal energizing the electro-active material. The resulting induced-strain displacement is kinematically amplified and then sent to the flight control surface input arm. A similar configuration can be devised for an induced-strain actuated flight control system using magneto-active materials by replacing the high-voltage power amplifier with a high-current power amplifier.

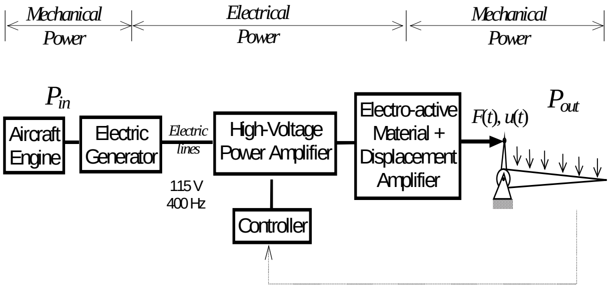

Figure 5 Schematic representation of an solid-state induced-strain actuated flight control system using electro-active materials.

There are several perceived benefits of the solid-state induced-strain flight control system when compared with the conventional (hydraulic based) flight control systems:

1. The power supply is electric, hence power can be sent much easier throughout the entire aircraft. The electric power delivery system is less prone to damage and does not suffer from the classical ailments of the hydraulic systems (leaks, bursts, gassing, etc.).
2. The demand signal generated by the controller can be directly fed into the flight control system without the need for an electro-mechano-hydraulic converter such as the servo-valve.
3. The solid-state induced-strain actuators based on electro-active (magneto-active) materials are electro-mechanically coupled through the piezo-electric (piezo-magnetic) effect, i.e. it generates mechanical power when activated electrically, and *vice-versa*. This aspect allows for a two-way power flow between the electrical input and the mechanical output, and opens attractive opportunities for energy recycling and power harvesting that are unattainable with the conventional hydraulic systems.

Solid-state induced-strain flight control systems also has several drawbacks that need to be addressed before they could truly compete with the conventional flight control systems:

1. The electro-active (magneto-active) induced-strain actuators present a predominantly reactive input impedance to the power amplifier. This means that, as opposed to traditional electric motors, the solid-state induced-strain actuators have a very small power factor value, typically $\cos\phi \approx 0.05 - 0.10$. This presents an unusual problem to the power amplifier designer who has to tackle efficiently the very large amounts of reactive power flowing into the solid-state induced-strain actuators.
2. The electro-active and magneto-active materials presently available for the fabrication of induced-strain actuators are brittle ceramics that need special mechanical design for their safe and reliable utilization.
3. The electro-mechanical coupling properties of presently available electro-active (magneto-active) materials are temperature dependent and hence the

actuators incorporating these materials may be affected by the severe temperatures encountered throughout the flight envelope (-50^{0}C to +80^{0}C).

2. MECHATRONICS ASPECTS

Mechatronics is an emerging engineering discipline that integrates the classical fields of mechanical engineering, electrical engineering, computer engineering, and information technology to establish basic principles for a contemporary engineering design methodology. Mechatronics supports the synergistic integration of precision mechanical engineering, electronics, controls, and systems thinking into the design of intelligent products and processes. Active materials induced strain actuation is a typical example of an interdisciplinary application that brings together electrical, mechanical, controls, and electronics specialties. Not only is the active material a quintessence representation of a coupled field concept, but also, in order to make it work, paraphernalia of electrical and electronic devices have to be integrated into a workable system. The most obvious and alas often overlook aspect is that of the power amplifiers.

Power amplifiers constitute an essential part of the smart materials induced-strain actuation solution, and a sizable portion of the required weight and volume required for its practical implementation. Conventional linear amplifiers are not designed for handling highly reactive loads, and are not suitable for induced-strain actuation applications. Linear amplifiers do not recycle the energy returned by the induced strain actuator during its contraction, but rather dissipate it to the thermal sinks. Thus, the reactive power returned from the actuator is lost. Since induce-strain actuators are essentially large capacitors or large inductors, i.e., reactive loads, a systemic design approach is needed that should incorporate amplifiers capable of reusing the reactive power and energy. Lidner and Chandrasekaran, (2000) and Clingman and Gamble (2000) reported work on switching amplifiers that are able to apply energy harvesting concepts to induced strain actuation. In this way, conservation of the reactive power can be achieved, and the actual power consumption required for effective actuation will be greatly minimized. Another mechatronics aspect to be considered is that of new coupled-field actuators that lately emerged, e.g., the high power electromechanical actuators described by Reithler, L. *et al.* (2000) and also by Fink *et al.* (2000). At the end of such a multidisciplinary optimization analysis, a conceptual design solution that optimizes the power and energy transmitted to the control surface can be developed. In the optimization process, means for reducing the size and weight of the power supply through integrated electronics must also be addressed. The problem of designing active-materials induced-strain actuation systems is a multidisciplinary design optimization problem that crosses over conventional engineering disciplines and is well lodged in the interdisciplinary field of mechatronics.

3. CONCLUSIONS

The electro-mechanically coupled operation of solid-state induced-strain actuators connected to flight control surfaces has been discussed. It has been shown that the power and energy management in induced-strain actuated adaptive control systems differs considerably from that of conventional flight control systems. The conventional flight control systems consume predominantly active power in spite of driving a predominantly reactive mechanical load represented by the aerodynamic control surface. The solid-state induced-strain actuated flight control system use predominantly reactive power and, through the electro-mechanically coupling with the aerodynamic control surface, open new opportunities for power recycling. It is conceivable that a properly tailored solid-state induced-strain-actuated control system will use an order of magnitude less power from the aircraft power supply than a conventional hydraulic system, and hence will effect considerable savings in power, energy and weight. However, new concepts for reactive power management in high-voltage high-current power amplifiers need to be developed, and high-efficiency airborne power amplifiers must be built. Such specialized high reactive-power amplifiers for solid-state induced-strain actuators should be the focus of future mechatronics research.

4. ACKNOWLEDGMENTS

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