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13. ABSTRACT (*Maximum 200 words*)
The use of smart materials for rotorcraft control surface actuation at laboratory scale has performed large strides forward and the scale up of these results from laboratory into prototype demonstrations is imminent and could happen in the near future. However, the introduction of the smart materials technology to missile controls is lagging behind. In this report we investigate the feasibility of using smart-materials technology for the missile fin control surfaces actuation from the required energy/power point of view. Due to the short-time, small-effort characteristics of the present project, our analysis was performed at fundamental concept level. A reduced maneuver envelope was defined at Mach 1 and zero AOA, defining the target values for the missile fin deflection, hinge moment, and actuation rate. We have also determined how these values translated into requirements for the energy and power of the smart material actuation device, under the conditions of various actuation signals. Further, we investigated if commercial-off-the-shelf (COTS) smart materials devices exist that could satisfy these requirements. The reported research showed that present COTS smart materials devices are able to meet the power/energy requirements and that optimal design of the displacement amplification mechanism can be performed.

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SMART-MATERIAL ACTUATED
MISSILE FLIGHT CONTROL SURFACES
FEASIBILITY STUDY

FINAL PROGRESS REPORT

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Foreword

The use of smart materials for rotorcraft control surface actuation at laboratory scale has performed large strides forward and the scale up of these results from laboratory into prototype demonstrations is imminent and could happen in the near future. However, the introduction of the smart materials technology to missile controls is lagging behind. Clear opportunities exist for transitioning the knowledge accumulated in the smart materials rotorcraft projects to missile control applications that would make the latter more agile, easier to control and less expensive.

Consistent work on model-scale active-material missile control surfaces was performed at the University of Auburn (Barret, 1993, 1996). The studies were mainly focused on developing active-material actuated missile fins. The initial experiments were valuable because they highlighted the challenges and opportunities associated with the use of smart materials for missile fin actuation. Though pioneering, these experiments were not able to achieve the desired actuation performance. During the wind tunnel experiments, sizable actuation angles could only be obtained at the mechanical resonance. The main reason for this behavior may lie in the basic lack of power and energy inherent the in selected smart materials actuation solution. A few piezoelectric patches fixed on an airfoil skin or on a flexspar simply do not have the needed energy contents to effect the required displacement when aerodynamics flow is present. A careful consideration of the steady and oscillatory aerodynamic loads associated with the missile fin movement, and the subsequent energy availability and energy transfer analysis performed on the actuator/displacement amplifier assembly is needed. Such an analysis, when performed, would reconcile the fundamentals at the beginning of the design cycle and ensure success of the prototype testing, in the laboratory, in the wind tunnel, and in actual flight.

In this report we address these fundamental questions and investigate the feasibility of using smart-materials technology for the missile fin control surfaces actuation from the required energy/power point of view. Due to the short-time, small-effort characteristics of the present project, our analysis was performed at fundamental concept level. A reduced maneuver envelope was defined at Mach 1 and zero AOA, defining the target values for the missile fin deflection, hinge moment, and actuation rate. We have also determined how these values translated into requirements for the energy and power of the smart material actuation device, under the conditions of various actuation signals. Further, we investigated if commercial-off-the-shelf (COTS) smart materials devices exist that could satisfy these requirements. The reported research showed that present COTS smart materials devices are able to meet the power/energy requirements and that optimal design of the displacement amplification mechanism can be performed.

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Statement of the problem studied

Objectives

The objective of the reported research was to evaluate the feasibility of using smart materials for actuating missile flight control surfaces.

Problem description

Reduced missile flight envelope

The missile control surfaces are subject to airstream forces and moments generated by two concurrent factors: (a) missile angle of attack (AOA); and (b) control deflection, δ (Figure 1). The angle of attack produces the quasi-static loading, over which the dynamic loading generated by the control deflection, δ, is superposed. The resulting airloads also depend on control surface geometry and Mach number. For current missile technology, the Mach number may vary from just subsonic ($M \leq 1$) to high supersonic ($M = 3$).

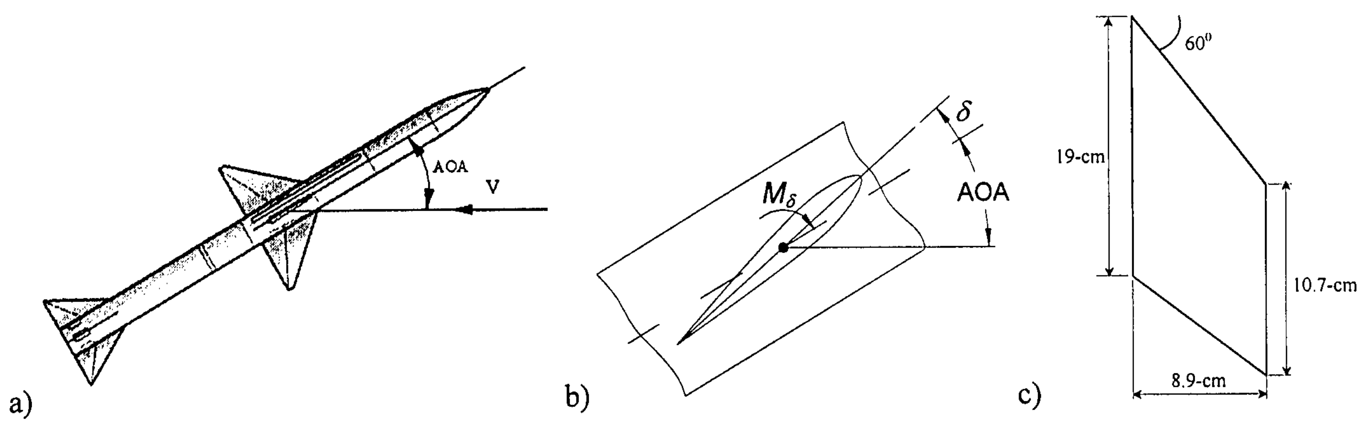

Figure 1 Missile control surface loads modeling: a) missile in flight; b) moment and deflection; c) fin plan form.

We considered a generic missile fin of 19-cm × 10.7-cm ×8.9-cm and 60-deg leading edge sweep (Figure 1).

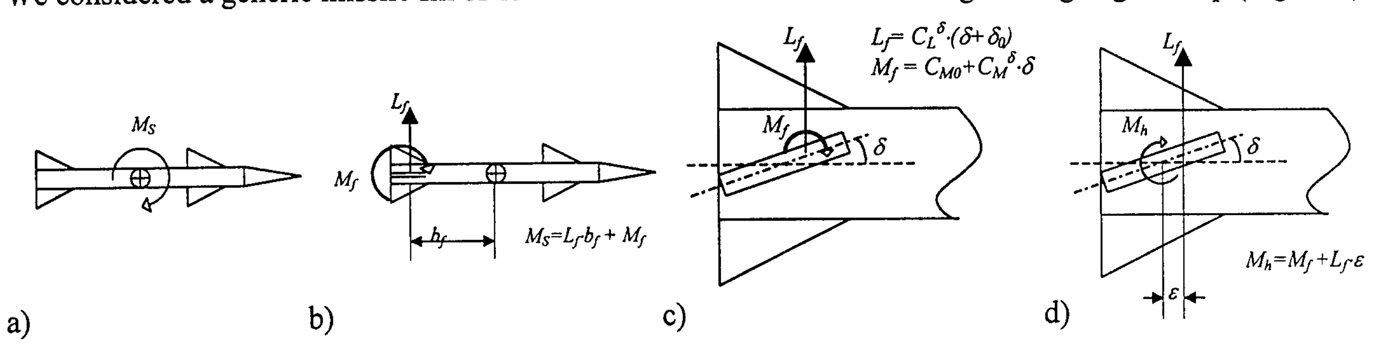

Figure 2 Steering moment delivery through missile fin deflection, at zero AOA

A required steering moment for maneuvering the missile M_S can be provided by the aerodynamic force and moment on the fin, L_f and M_f respectively (Figure 2, (a) and (b)). For high AOA and supersonic Mach, the drag contribution to the steering moment should also be taken into account. Based on the equations presented in Figure 2, the hinge moment can be related to the required steering moment as follows:

$$M_h = M_S \frac{\varepsilon}{b_f}\left[1+\left(\frac{b_f}{\varepsilon}-1\right)\frac{C_M^\delta}{C_M^\delta + b_f C_L^\delta}\right]$$

For a symmetric profile at zero angle of attack (AOA), the hinge moment M_h can be expressed as a linear function of the missile fin deflection δ:

$$M_h = \delta\left(\varepsilon \cdot C_L^\delta + C_M^\delta\right)$$

The quantitative plot of the above equation shows the spring-like behavior of the aerodynamic control surface (Figure 3). A reduced actuation envelope (hinge moment *vs.* fin deflection), achievable with commercially-off-the-shelf (COTS) smart materials actuators, was identified based on the required steering moment (Table 1).

Table 1 Preliminary requirements for a smart-materials actuated missile fin

Moment	$M_{peak} = 2.5$ Nm ;
Deflection	$\delta = +/- 3$ deg.
Rate	$\dot{\delta} = 3.5$ rad/s

In order to meet the missile fin actuation requirements, one has to investigate both the actuation type (e.g. sinusoidal, step, etc.) and the capability of the COTS devices.

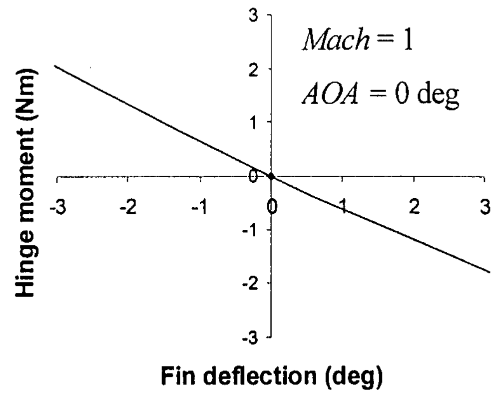

Figure 3 Moment-deflection diagram for AOA = 0^0

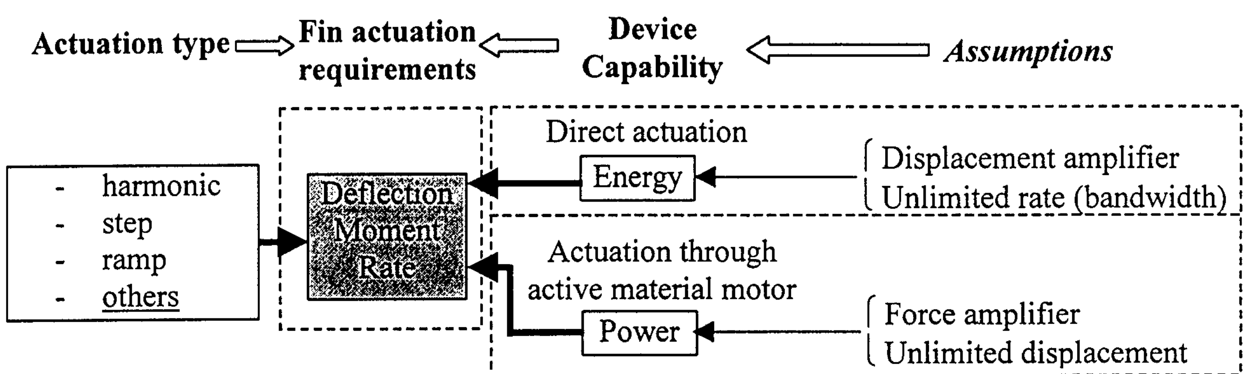

Figure 4 Meeting the requirements involves input signal design and smart-materials device capabilities

Sine, ramp and step input signal requirements for missile fin actuation

The actuation of the missile fin can be done using harmonic, step, or ramp excitations. Alternatively, special amplitude-modulated signals can be used to meet the power requirements. The variations of the required energy and power within a cycle for the above-mentioned excitations are used to determine whether COTS smart materials devices are capable of actuating the missile fin with a given input signal (Figure 5).

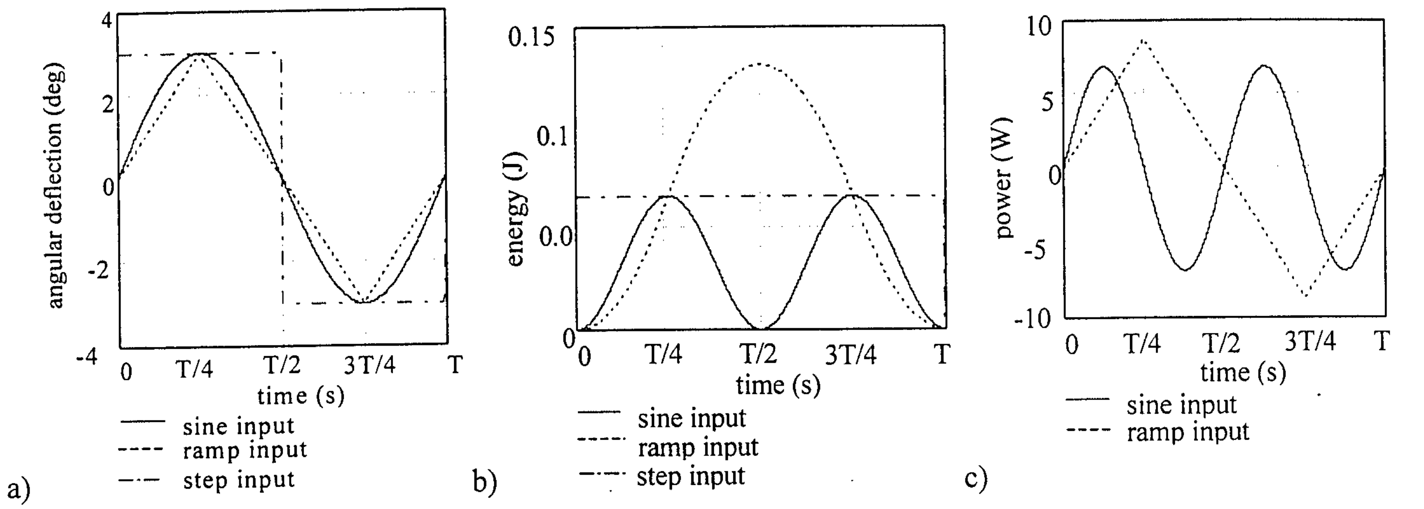

Figure 5 Variation of the required actuation energy and power within a cycle: a) input signal; b) required energy within a cycle; c) required power within a cycle

The peak values in terms of required energy and power (Table 2) were compared with the energy/power capabilities of the COTS smart material devices.

Table 2 Preliminary requirements for a smart-materials actuated missile fine

	Sine actuation	Ramp actuation	Step actuation
Peak energy per cycle	$E_{peak} = \frac{1}{2} M_{peak} \delta_{peak}$ $= 0.065$ J	$E_{peak} = M_{peak} \delta_{peak}$ $= 0.13$ J	$E_{peak} = M_{peak} \delta_{peak}$ $= 0.13$ J
Peak power per cycle	$P_{peak} = E_{peak} \cdot \frac{\pi \cdot \dot{\delta}}{2\delta_p}$ $= 6.87$ W	$P_{peak} = M_{peak} \dot{\delta}$ $= 8.75$ W	–

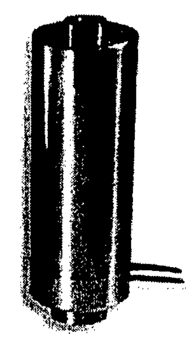

Figure 6 Physik Instrumente P-245.70 PZT actuator

Induced strain actuation smart materials device capabilities

We have identified two design concepts that employ the smart materials technology to missile fin actuation. The direct actuation concept uses active material stacks (Figure 4) via a displacement amplification mechanism in order to produce sizable displacements of the actuated structure (Figure 6). This approach has the advantage of the very high frequency response, and high forces specific to smart material stacks. Thus, the most significant metric when comparing direct actuation is maximum energy available from the smart material device. The limitation on the available power comes mostly from the power amplifier maximum current capabilities.

Another design concept uses the smart-materials motors that offer the advantage of far greater displacement output than smart-material stack of comparable mass and volume (Figure 7). The higher energy density of smart-material motors is attributed to the "frequency rectification" or "power ratcheting" concepts, whereby the considerable energy magnification per cycle is obtained through frequency devolution within the power conservation principle.

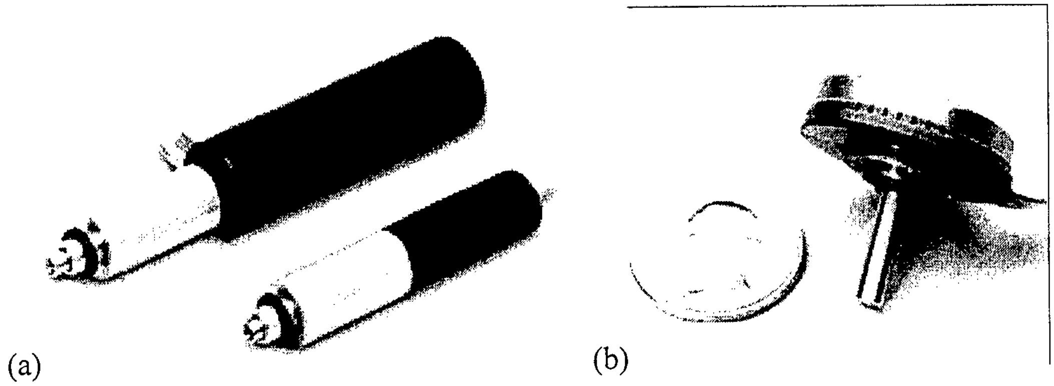

Figure 7 a) Burleigh Inchworm Linear Motors; b) Piezo Systems Ultrasonic Motor

Displacement amplification concepts

The inherent small strains capabilities of the smart material devices make necessary a displacement amplification mechanism for the case of direct actuation. A simple model (Figure 8) was consider, that transforms the linear motion of the active material device into rotary motion needed for the actuation of the missile fin. This model considered the displacement amplification mechanism as a black box with 2 variables: the gain G and the work efficiency η_m, defined as:

$$G = \frac{u_e}{u_e'} \qquad \eta_m = \frac{F_e \cdot u_e}{F_e' \cdot u_e'}$$

We have performed feasibility calculations using the preliminary requirements outlined in Table 1 and the actuation scheme shown in Figure 8, with $r_0 = 5$ mm.

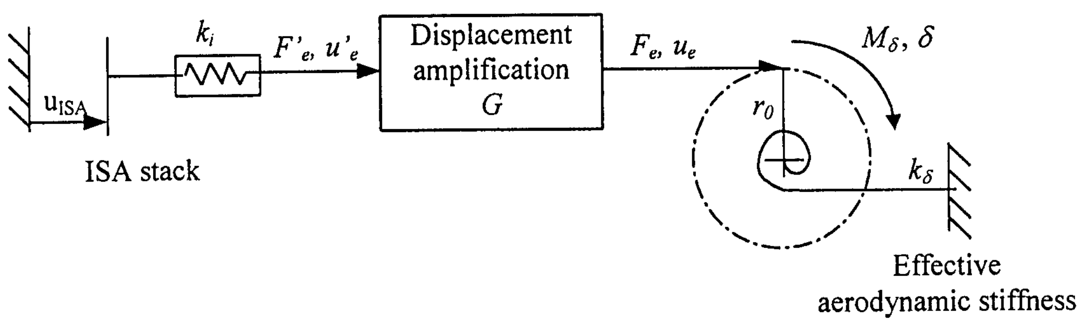

Figure 8 Schematic drawing of the displacement amplification process

Summary of the most important results

How the COTS smart material devices meet the reduced envelope requirements

We have compared the preliminary requirements of the reduced envelope with the maximum attainable performances of the active material devices, using information from manufacturers.

The results of this comparison for the direct actuation of the missile fin show that the required energy values fall within the capabilities of commercially available smart materials actuators for both sine and ramp actuation (Figure 9a). Due to the large bandwidth of the direct actuation devices, meeting the energy requirements ensures the capability of satisfying the power requirements. This statement is true within the limitations of the power amplifiers of providing the required input signal (i.e. shape, maximum value and frequency) to the load represented by the smart material devices.

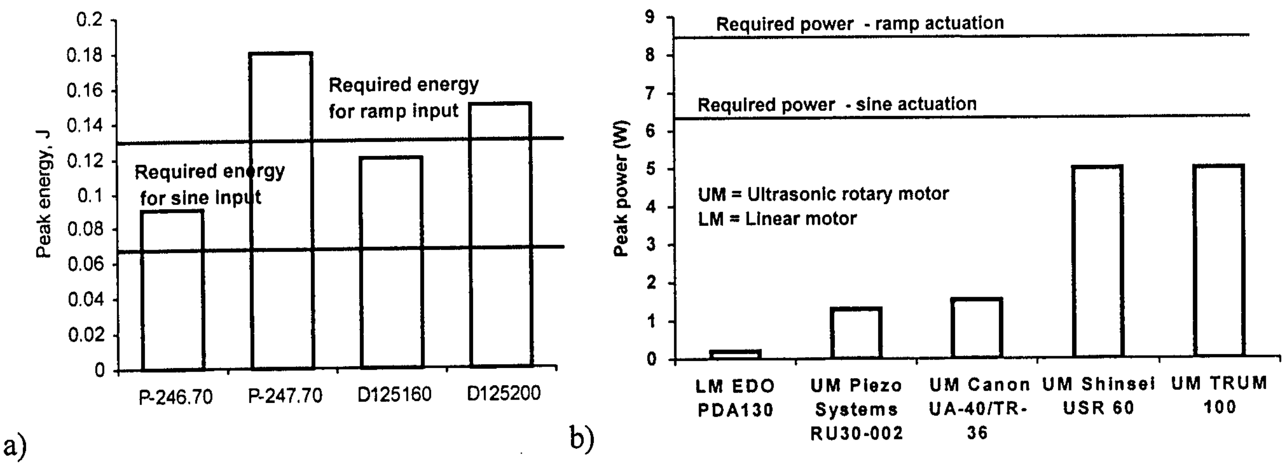

Figure 9 Present commercially available actuators meeting the missile fin reduced envelope energy requirements: a) comparison of the direct actuation devices deliverable energy with the required energy for sine and ramp input; b) comparison of the smart materials motors maximum deliverable power with the required power for sine and ramp excitations

Comparison of smart materials motors power capabilities with the threshold values given by the power peaks in Figure 5c shows that both up-to-date COTS linear and ultrasonic rotary motors fell short of fulfilling the power requirements (Figure 9b).

New trends in smart materials motors are pursued in order to achieve more power at the same or lower cost as the rotary ultrasonic motors. One direction researched at the Pennsylvania State University is represented by the mechanically diode based high-torque piezoelectric rotary motor, with a measured peak-power of 3.7 Watts (Lesieutre *et al.*, 2001). This direction may lead to even higher power capabilities through the bipolar excitation of the bending bimorphs that actuate the rotary roller clutch.

Design of the optimum gain/energy-transfer displacement-amplification mechanism

The design of a displacement amplifier for the case of direct actuation must address several other parameters besides the required energy output. This is mainly because of the necessity of a displacement amplifier with a non-ideal, smaller-than-unity energy transmission efficiency. For example, if we use the Physik Instrumente P245–70 actuator and model the aerodynamic response solely as a spring system, the displacement amplification shown schematically in Figure 8 should have the energy transfer efficiency η_m in excess of 0.36, while for the Kinetics Ceramics D12200 actuator, η_m should be greater than 0.42. These requirements outline the need to choose another design metric specific to the design amplification mechanism, besides the energy transfer coefficient which is a smart material device characteristic.

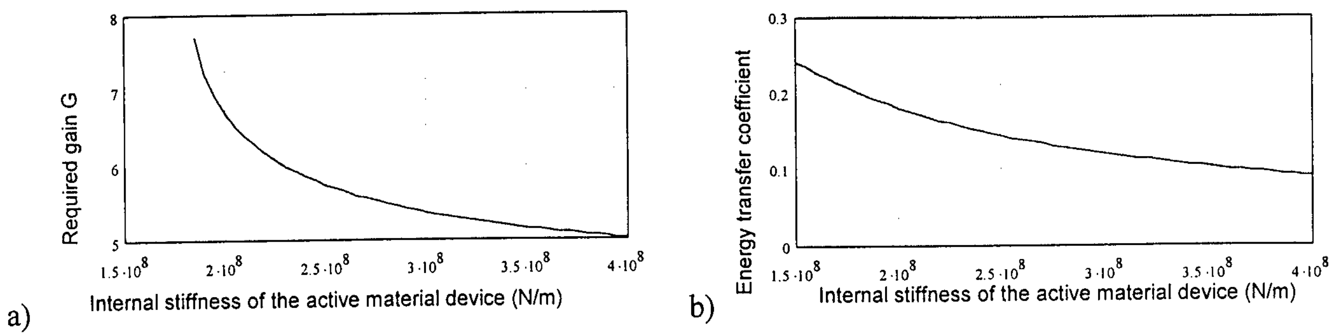

Figure 10 Variation of the required gain G and energy transfer coefficient with the internal stiffness of the actuator, considering the displacement amplification efficiency η_m=0.8.

If the direct actuation device is not specified, the internal stiffness of the actuator can be considered as a design parameter. In Figure 10 we have illustrated the dependence of gain and energy transfer coefficient, defined as the ratio of the available energy to the maximum deliverable energy, with the internal stiffness of the actuator.

The gain and the energy transfer coefficient are further given by

$$G = \eta_m \cdot \frac{1-\sqrt{1-4\cdot\dfrac{r\cdot\eta^2}{\eta_m}}}{2\cdot r\cdot\eta}$$

$$E'_e = \frac{\frac{1}{2}k_\delta\delta^2}{\frac{1}{2}k_i u_{ISA}^2} = \frac{r\cdot G^2}{\left(1+r\cdot\dfrac{G^2}{\eta_m^2}\right)^2}$$

where η is the kinematic gain, defined as $\delta r_o / u_{ISA}$, and u_{ISA} is the maximum induced-strain displacement.

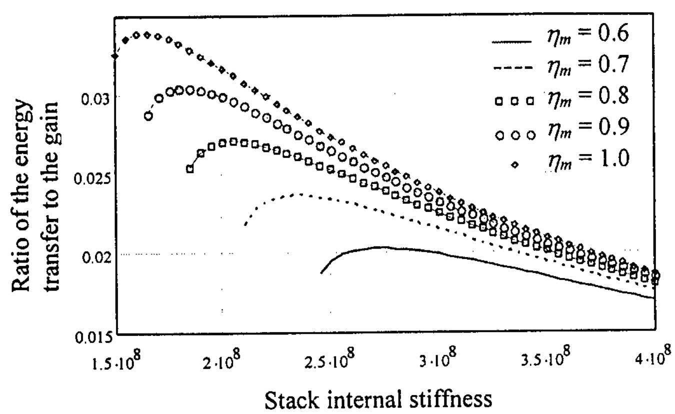

Figure 11 Variation of the optimum metric $R=E_e'/G$ with the internal stiffness and the displacement amplification mechanism efficiency

Since an optimal design should tend toward minimum gain and maximum transfer energy, it is apparent from Figure 10 that an optimum point can be achieved. If we define the metric to characterize the optimum point as the ratio of the energy transfer coefficient to the gain of the displacement amplification mechanism, an optimal internal stiffness can be found for any allowed energy transfer efficiency (Figure 11).

List of all publications and technical reports

Giurgiutiu, V., "Smart-Material Actuated Missile Flight Control Feasibility Study", Final Progress Report

Giurgiutiu, V., Pomirleanu R., Rogers C. A., "Energy-Based Comparison of Solid-State Actuators", Report #USC-ME-LAMSS-2000-102, March 1, 2000.

Giurgiutiu, V., Pomirleanu R., Padgett D., "Modeling and Characterization of Piezoelectric and Magnetostrictive Induced Strain Actuators", 37th Annual Technical Meeting Society of Engineering Science, October 23-25, 2000.

List of all participating scientific personnel showing any advanced degrees earned by them while employed in the project

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Appendixes

None.