EXPERIMENTAL STUDY OF A HYDRAULICALLY-AMPLIFIED, HIGH DISPLACEMENT, INDUCED-STRAIN ACTUATORS, PROOF OF CONCEPT DEMONSTRATOR

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ABSTRACT

A rotor blade trailing edge flap actuation device, HAHDIS (Hydraulically-Amplified, High-Displacement, Induced-Strain Actuator), driven by two high-displacement induced-strain actuators (ISA), has been built and tested at the Center for Intelligent Materials Systems and Structures. The input displacements of the two solid-state piezoceramic ISA are hydraulically amplified and the linear output displacement is transformed, through a kinematic linkage, into the angular deflection of an aircraft servo-tab.

The paper presents the experimental tests and results. The data collected was processed to yield the electrical input energy and mechanical output energy as well as the displacement frequency response of the tab, over the 1-30 Hz frequency range. Good output force, work and displacement frequency responses were recorded over the frequency range of interest. Limitations in the electrical power supply capabilities were identified to be causing response losses at higher driving frequencies.

INTRODUCTION

Rotor blade vibration and noise reduction, based on higher harmonic control (HHC) or individual blade control (IBC), has been identified as a potential area for application for induced strain actuators (ISA), (Straub, 1995), (Giurgiutiu et al., 1995f), (Dadone, 1995). Traditionally, helicopter vibration has been controlled through the use of passive isolators and absorbers. These classical vibration absorbing devices have performance and weight penalties, however. Previous papers have demonstrated the benefits of using trailing edge (TE) flaps to reduce rotorcraft blade vibration (Millot and Friedmann, 1992) and noise (Niesl, 1994). The trailing edge flap modifies the aerodynamic loads on the blades, thus canceling vibration. Different servo-flap configurations have been investigated in the literature and, as a result, several displacement and power requirements were found. However, a common ground for all these requirements was recommended (Giurgiutiu et al., 1995f).

Direct implementation of the ISA servo-flap actuation without a displacement amplifier has been shown not to be feasible, due to small strains inherent to such actuators. Indirect actuation through a displacement amplifier was found to be feasible and several amplification methods may be found throughout the available literature.

The focus of the research presented in the current paper was to determine the power budget (input electrical energy versus output mechanical energy). The HAHDIS device, (Giurgiutiu et al., 1996 a,b), used two PMN induced strain actuators to drive an aircraft flap. The small linear deflections of the ISA actuators were hydraulically amplified and used to actuate the flap. A kinematic linkage was used to transform the linear output displacement into the angular flap deflection.

EXPERIMENTAL SETUP

For dynamic testing, four EDO Corporation E300-P4 PMN stacks, grouped in two serial pairs, were used to drive the HAHDIS actuator. The resulting stacks had 0.120 mm free displacement and 80 kN/mm internal stiffness. They were placed at the reciprocal-acting input cylinders of the HAHDIS Mk.1 device.

The device was dynamically tested over a discrete range of frequencies from 1 to 30 Hz, in increments of 1 Hz. The PMN stacks were energized with a pair of high voltage sinusoidal signals (400+/-400 V) produced by a dual channel model 50/750 TREK high voltage amplifier. The two signals were in opposite phase though maintaining the same bias. This arrangement permits one stack to expand while the other retreats. The hydraulic fluid was pushed back and forth from
one chamber to another, resulting in an alternating linear motion of the output piston.

The main problem encountered throughout the experiments was the current power limitations of the power supply.

POWER ISSUES FOR THE FREE PMN ACTUATOR

In this experimental part, the intensity of the current passing through one free (unloaded) PMN actuator was measured. One of the PMN actuators was energized with a high voltage sinusoidal signal (400+/−400 V). A 1.4 ohm probe resistance ($R_P$) was linked in series with the PMN stack and the voltage on the resistor was measured with an oscilloscope. The experimental setup used in the experiment is presented in Figure 1.

![Figure 1. Experimental setup for the measurement of the current passing through a free ISA](image)

The symbol $E$ denotes the power source. With the help of an impedance analyzer, the modulus and phase of the actuator impedance were determined. Then, the actuator was approximated with a series RC equivalent circuit, since at low frequencies the actuator acts as an almost pure capacitor. The impedance analyzer found the equivalent capacitance of the actuator to be $C_A=2.826 \mu F$ and the resistance $R_A=8.496 \Omega$. The introduction of the probe resistor $R_P$ in the electrical scheme has not modified significantly the phase angle $\phi$ between the current and the voltage, as the following calculations show. For an RC circuit, the phase angle is equal to the inverse tangent of the ratio of the imaginary part to the real part of the circuit impedance ($f$ is the frequency of the current):

$$\phi = \tan\left(-\frac{X_C}{R_P}\right) = \tan\left(-\frac{1}{2\pi fC_A(R_A + R_P)}\right)$$

(1)

The phase angle varies only minutely with the frequency of the current: at 1 Hz, the phase angle $\phi$ is $-89.998^\circ$ and at 30 Hz is $-89.96^\circ$ (from Equation 1). Phase angles were also determined experimentally, with an oscilloscope and good agreement with the theory was found. Figure 2 shows the calculated variation of the phase angle with the driving frequency.

![Figure 2. Phase angle between voltage and current supplied to loaded ISA vs frequency](image)

The current passing through a free ISA, as a function of frequency, is shown in Figure 3.

![Figure 3. Experimental measurement of the current passing through free ISA vs frequency](image)
From Figure 3, it may be seen that the current reached its maximum value of 93.71 mA at 8 Hz frequency, due to limitations of the power amplifier. At driving frequencies above 14 Hz, the voltage supplied to the stack started to ease. The nominal supply value began to decrease after 14 Hz. As a result, the amplitude of the power supplied to the free stack also decreased. Figure 4 shows the variation of the supply voltage with the driving frequency. The power limitations appeared even when the PMN stack was not working in the HAHOIS device.

![Figure 4. Voltage Supplied to Free ISA vs Frequency](image)

The active power used by the "free" PMN stack is:

\[ P_A = I \cdot V \cdot \cos \phi \]  

Equation (2)

The amplitude of the voltage is V and I is the amplitude of the supply current.

The amplitude of the reactive power is, in case of a bias voltage \( V_{bias} \), (Giurgiutiu et al. 1996):

\[ P_R = I \cdot V \cdot (1 + 1.62 \frac{|V_{bias}|}{V}) \]  

Equation (3)

Thus, the active power and the maximum instantaneous active and reactive power used by the actuator are computed and are presented in Figure 4 and Figure 5, respectively.

![Figure 5. Active Power, for the Free Induced Strain Actuator, vs Frequency](image)

It may be observed from Figure 6 that the reactive power used by the stack reached a maximum in the 8 to 14 Hz frequency range, after which it decreased, due to the power supply limitations. The active power increased continuously up to a certain level, even though the power limitations appeared. This behavior is due to the change in the voltage-current phase angle, to which the active power is very sensitive. From Figure 5 and 6, it may be seen that the maximum instantaneous reactive power is much larger than the maximum instantaneous active power.

![Figure 6. Maximum Instantaneous Reactive Power, for the Free Induced Strain Actuator, vs Frequency](image)
POWER ISSUES FOR THE HAHDIS ACTUATOR

The impedance of a PMN actuator piezo-stack varies if the actuator is subjected to a mechanical load. The actuators are preloaded with a force corresponding to a pressure of 140 psi, in the hydraulic amplifier, and then activated with biased ($V_{bias} = +400$ V) sinusoidal voltage from 0 to $+800$ V. The same electrical setup, as shown in Figure 1, was used to determine the current passing through the PMN stack. Next, the work done by the actuator had to be found. The experimental setup is shown in Figure 7.

![Figure 7. Output work and force experimental setup](image)

The output piston pushed against a 30 lb. force gauge. The force gauge was initially preloaded by the output piston with a 1 lb. force that ensured continuous contact between the piston and the force gauge during the experiment. The force and the displacement of the output piston were multiplied (in the DTVEE 3.0 data acquisition software) to yield the output work. The supply voltage, electrical current and phase between the voltage and current were measured with the help of an oscilloscope and an HP4194A impedance analyzer. The variation of the current with the driving frequency is shown in Figure 8. The same limitations in the power supply capabilities are observed after 8 Hz. After 8 Hz, the current waveform became square (instead of sinusoidal) in shape, and displayed nonlinear behavior. Figure 9 shows the variation of supplied voltage with the driving frequency. The magnitude of the voltage signal decayed after the frequency reached the 12 Hz threshold. The shape of the voltage waveform became increasingly angular, instead of remaining sinusoidal. The phase angle between the current and supply voltage did not vary much from the $-90^\circ$ value. However, the phase angles values for the loaded PMN stack were a little lower in modulus, compared to the "free" ISA phase angle values. The phase angle, between the PMN current and supply voltage are shown in Figure 10.

![Figure 8. Current passing through ISA under load vs frequency](image)

![Figure 9. Voltage supplied to loaded ISA vs frequency](image)
The real and imaginary components of the active and reactive power are shown in Figure 11 and, respectively, in Figure 12.

The variation of the reactive and active power with frequency for the loaded PZT, displayed the same behavior as the variation of the reactive and active power with frequency for the "free" PZT. The reactive power increased and maintained its peak value and then, after a 12 Hz frequency threshold began to decrease. The peak reactive power value was maintained for a smaller frequency range than in the "free" stack case. The active power increased almost continuously with the frequency. From Figure 11 and 12, it may be again seen that the maximum instantaneous reactive power is much larger than the active power.

A sample of the data acquisition screen for the output force and work, captured at 8 Hz, are shown in Figure 13 and Figure 14, respectively.
FIGURE 14. OUTPUT WORK WAVEFORM CAPTURED AT 9 HZ

The output energy amplitude of a mechanical device may be written as:

\[ E = 0.5 \cdot F \cdot U \]

where \( U \) is the output displacement and \( F \) is the output force. The amplitude of the output piston force and the output energy amplitude are shown in Figure 15 and Figure 16, respectively.

FIGURE 15. OUTPUT FORCE AMPLITUDE VS FREQUENCY

As was observed in the previous section, the supply voltage reached its peak around 8 Hz. The output force and the output work reached their peak value at 10 Hz and 9 Hz, respectively. Thus, the power output work and force were not displayed for frequencies greater than 10 Hz.

FIGURE 16. OUTPUT WORK AMPLITUDE VS FREQUENCY

DISCUSSION AND CONCLUSIONS
The power and energy issues for induced-strain actuated adaptive control systems differs considerably from that of conventional flight control systems. The solid-state induced-strain actuated flight control system use predominantly reactive power. Over the range of frequencies investigated in our experiments, the active power used is almost negligible when compared to the reactive power. The phase angle between the supply voltage and current varied very little between the load case and the "free" load case. The output force values were encouraging, especially considering the force frictional losses occurring between the output piston and the seal. The output work is small due to the high stiffness of the force gauge and, obviously, to the friction losses. The waveform of the output work and force maintained their quasi-sinusoidal shape through the frequency range of interest and proved the controllability of the actuator.

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REFERENCES


