# Active Vibration Suppression

## using

## NiTiNOL Sensors and Actuators

by

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## ABSTRACT

This work investigates the development of NiTiNOL Shape Memory Alloys (SMA) sensors and actuators as components of an active vibration control system. Analytical and experimental models were developed and tested. The test set-up consisted of an aluminum cantilever beam with distributed NiTiNOL wires fastened along both sides. A constant amplitude control algorithm was used to provide a rate feedback force to actively suppress transient vibrations. The settling time of the beam was reduced by a factor of 15 through the use of the NiTiNOL wire sensors and actuators. Analytical simulations were developed which correlated well with the experimental results. This investigation demonstrated the feasibility of using NiTiNOL sensors and actuators for vibration suppression of structural members.

# INTRODUCTION

Future large spacecraft missions will require improved structural performance to meet serious vibration and control issues. Active vibration suppression, and pointing and shape control techniques will have to be developed to accurately control and monitor these large flexible space structures in the space environment. The overall spacecraft design will rely on distributed structural control methods to minimize local vibration and jitter, and maintain the high accuracy pointing and shape requirements. Structural members which contain their own local sensors, actuators, and computational/control capabilities need to be investigated.

Current state-of-the-art sensors and actuators are being researched industry wide. New design concepts are using electro-rheological fluids[1], piezoelectric ceramics[2], and shape memory alloys as methods of actuation. Some of these same designs involving piezoelectric ceramics and shape memory alloys along with other concepts that use fiberoptics[3] and acoustic waveguides[4] are being developed for sensing.

The focus of this paper is to investigate the feasibility of using shape memory alloy materials for both local sensing and actuation to minimize vibrations of a simple structure. The preliminary results of this investigation verify that shape memory materials can be used for vibration suppression.

# SHAPE MEMORY PROCESS

Shape Memory Alloy materials are generally provided in a basic shape (i.e. wire, rod, tube, sheet, etc.), from which the desired memory shape is constructed. The memory shape is physically constrained and annealed (heat treated) under a controlled environment to provide a permanent set. Once the material is annealed it is ready for operation. The SMA can be strained up to 8% of its original shape. This condition is usually known as the Martensite or soft condition. To return the SMA back to its memory set, heat is applied. After enough heat is added to reach the transition temperature the SMA will revert back to the memory shape with high energy release. This condition is usually referred to as the Austenite or hard condition. Once this transition has occurred heat is removed and the SMA can again be strained. This cycle is repeatable between soft and hard conditions.

# EXPERIMENTAL TEST STRUCTURE

A thin flexible cantilever beam was selected as the representative test structure with NiTiNOL wires mounted externally along the beam for both sensing and actuation (see figure 1). The test set-up was designed for low frequency (approximately 1 Hz) testing such that the actuation of the NiTiNOL wire could comfortly be cycled without bandwidth limitations. Table 1 lists the beam properties of the test structure used. Standard 55-NiTiNOL was used for actuation. Two actuator wires are used to control the 1st bending mode of the beam. A 10-mil wire was determined to provide sufficient actuation force as reported from the literature in figure 2. For two-way memory operation the stroke is usually limited to about 3-4% of the total wire length.
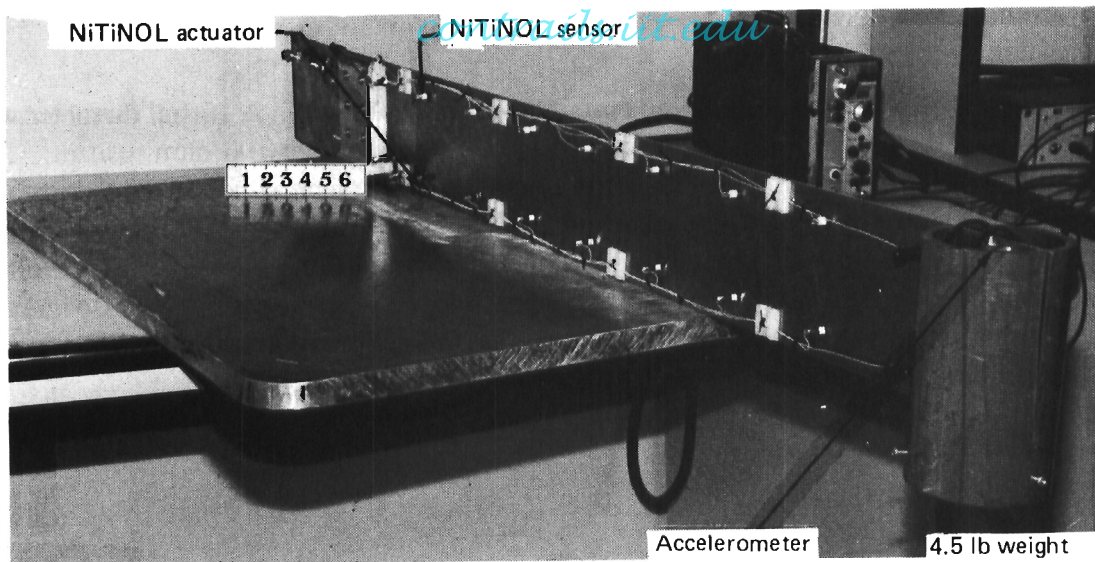
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*Figure 1. Cantilever Beam With NiTiNOL Wires*

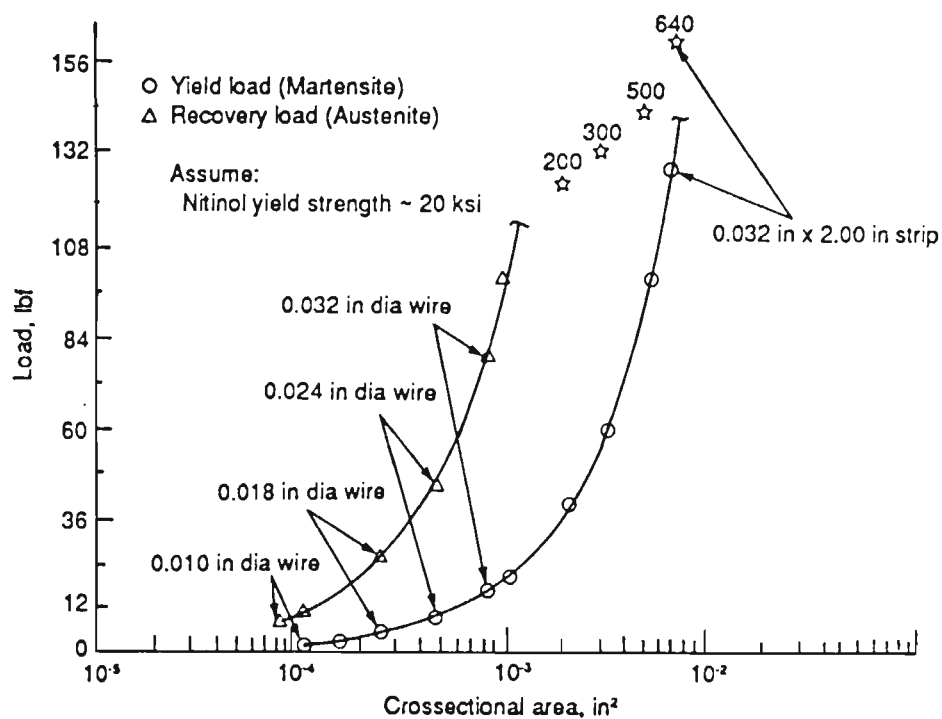| Material | Aluminum |
|---|---|
| Modulus | 11.0 Msi |
| Length | 48.00 inches |
| Thcikness | 0.125 inches |
| Width | 6.00 inches |
| Tip Mass | 4.5 lbs |
| Density | 0.10 lb/in² |
| Damping factor | 0.002 |

*Table 1. Beam Properties*



*Figure 2. NiTiNOL Load vs. Cross-Sectional Area (Recovery and Yield) from the Literature*

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# ANALOG CONTROL SYSTEM

The analog controlled NiTiNOL active damping circuit is shown in figure 3. A 10-mil diameter wire NiTiNOL sensor was activated with current from a 15v supply through an 100 ohm resistor. This provided about 100 ma of sensor current. As the beam deflected, the resistance of the NiTiNOL increased or decreased, causing a change of voltage across the sensor. The voltage across the sensor was detected with an high gain differential amplifier, the sensor was connected through capacitors so the DC voltage across the sensor would be ignored and any very slow changes due to temperature drift were also ignored. High frequency noise and spurious beam oscillations were also filtered out. Only dynamic voltage changes that correspond to the cantilever beam fundamental frequency were sensed.
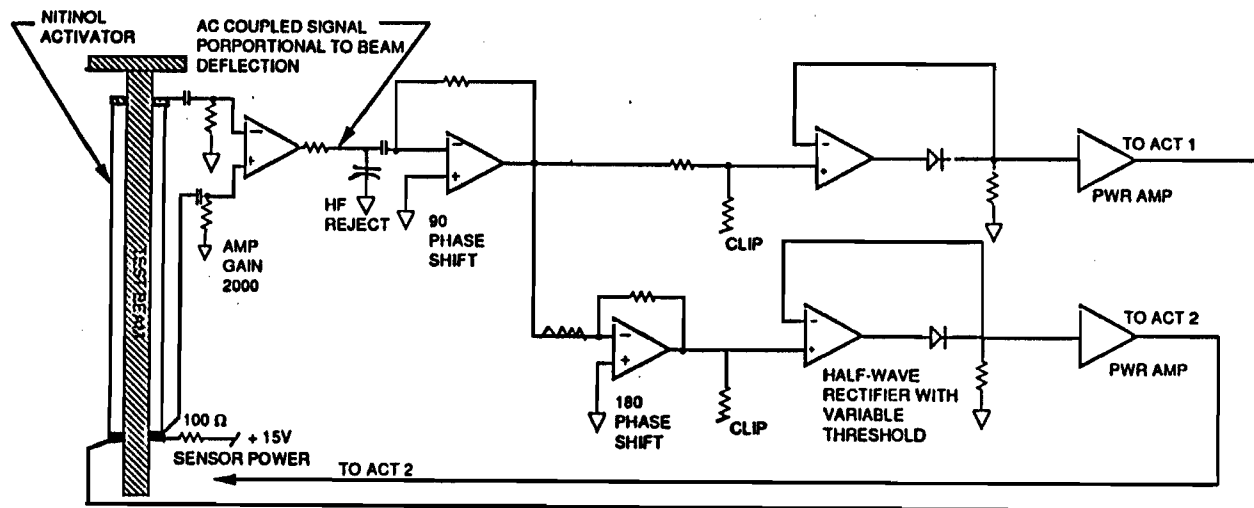


*Figure 3. Analog-Controlled NiTiNOL Active Damping Circuit*

The voltage out of the sensor was proportional to the length of the sensor wire or beam position. The maximum output was detected at minimum beam tip velocity. By differentiating the position signal a new signal was derived that was proportional to the velocity. In order to damp the beam oscillations, a force was applied to the beam to add a velocity vector opposite the existing beam velocity. This was intended to reduce the maximum beam velocity. Since a signal proportional to velocity was derived, it was most convenient to apply this force during the time of maximum velocity.

The velocity signal was sent to a rectifier. In parallel it was inverted and sent to a second rectifier. This circuitry provided two out-of-phase sine shaped pulse signals (see figure 4). These pulses were amplified using bench-type power amplifiers and applied to the NiTiNOL actuators. Note that power was applied alternatively to each actuator. While one was heating, the other was cooling (ambient room temperature). The clip adjustment was used to adjust the width of the heating pulses and the dead band.
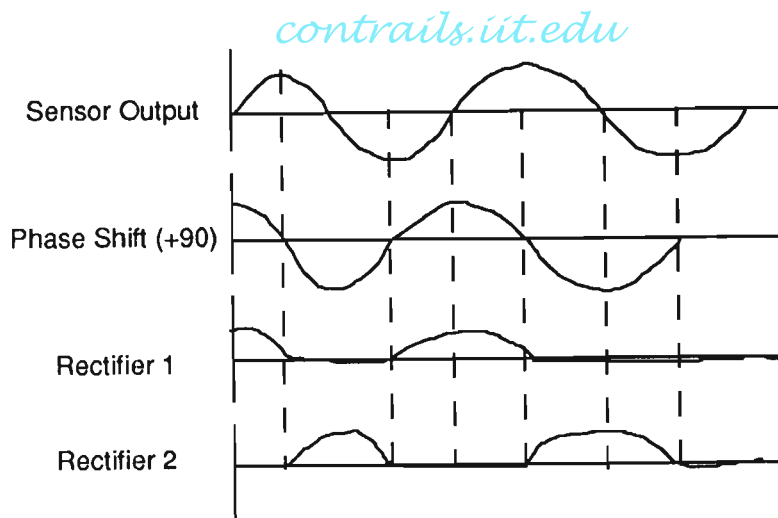
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*Figure 4. NiTiNOL Analog Control Signals*

## EXPERIMENTAL RESULTS

The effectiveness of the analog-controlled active vibration suppression circuit was evaluated by comparing the transient responses of the beam both with and without active vibration control. The tip of the beam was displaced a known distance (6 inches) and released. This test was performed first without any actuator or sensor wires attached. The beam took 7 minutes to naturally dampen out the oscillations. After the NiTiNOL wires were attached the beam was tested again and due to the high specific damping capacity of NiTiNOL [5] the beam passively damped out the oscillations in 4 minutes and 10 seconds. Figure 5 shows the oscilloscope readout of the transient response. Finally the test was repeated with the analog-controlled damping circuit activated the beam actively damped out the oscillations in 28 seconds. Figure 6 shows the oscilloscope readout of the transient response.
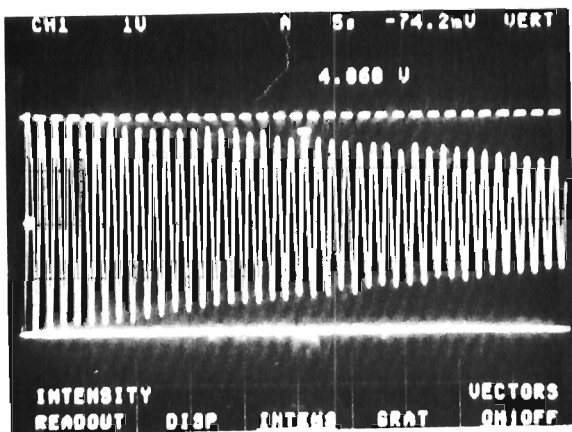


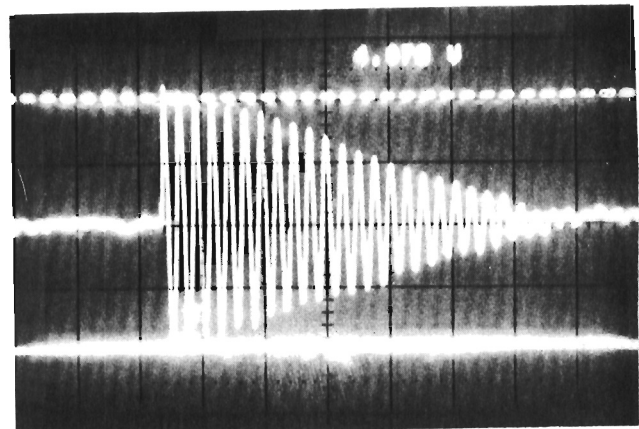*Figure 5. NiTiNOL Passive Damping System, 4 min, 10 sec*

*Figure 6. NiTiNOL Activee Damping System, 28 sec*

## SENSOR COMPARISONS

A standard strain gage type accelerometer was mounted at the tip of the beam. The NiTiNOL signal was differentiated twice to obtain a complimentary signal for comparison. Figure 7 shows an oscilloscope readout of transient beam vibrations using both the NiTiNOL wire sensor and the strain-gage type accelerometer. This comparison demonstrates the high level of resolution available from a NiTiNOL sensor. Because the NiTiNOL wire was strung the total length of the beam, sensor readouts could be taken at any point. To obtain this same capability using accelerometers, several would have to be placed at the desired discrete locations.

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NiTiNOL sensor
first harmonic
(acceleration)
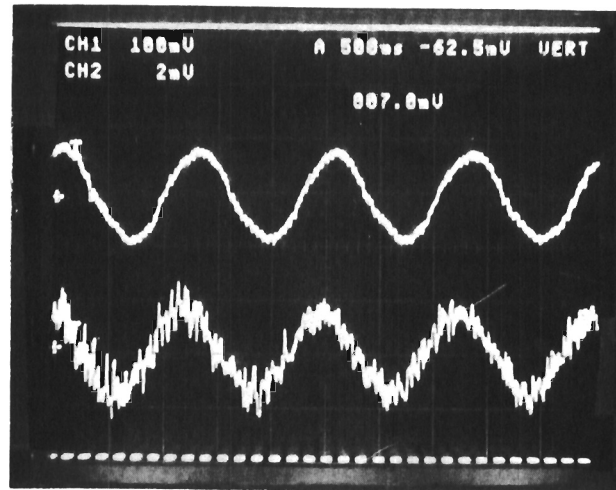
Strain gage
accelerometer

*Figure 7. NiTiNOL Cantilever Beam Sensor Comparisons*

## SIMULATION MODEL AND RESULTS

A simple simulation model was developed to help predict the damping effectiveness that could be achieved. A 20 node NASTRAN model was used to find the eigenvalues and eigenvectors. The first two bending modes of interest were;

$$f_1 = 0.73 \text{ Hz}, \omega_1 = 4.58659 \text{ rad/sec}$$
$$f_2 = 8.20 \text{ Hz}, \omega_2 = 51.5206 \text{ rad/sec}$$

The standard second order differential equation used to represent transverse vibration is given by [6]:

$$m\ddot{x} + kx = F \tag{1}$$

introduce the coordinate transformation

$$x = \phi q \tag{2}$$

where q are modal coordinates and $\phi$ the eigenvectors.

by substituting equation (2) into (1) and introducing modal damping yields:

$$[M]\{\ddot{q}\} + [C]\{\dot{q}\} + [K\{q\} = \phi^T F$$

where

M is the identity modal mass matrix
C is $2\zeta\omega_i$ diagonal damping matrix    i=1,2
K is $\omega_i^2$ diagonal stiffness matrix    i=1,2

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Based on the experimental response the NiTiNOL actuator was modelled using dry friction;

$$F = f \; \dot{x}/|\dot{x}|$$

where

f = constant magnitude force = 7.5 lbs/NiTiNOL wire.

Figure 8 shows the predicted tip position response which agrees with the experimental data discussed previously. Figure 9 shows the predicted tip position response for 4 NiTiNOL actuator wires, with a settling time of 16 seconds. Although the 1st mode was well behaved the second mode showed no influence from the 1st mode control (figure 10). For multiple mode control, actuator distribution becomes significant.
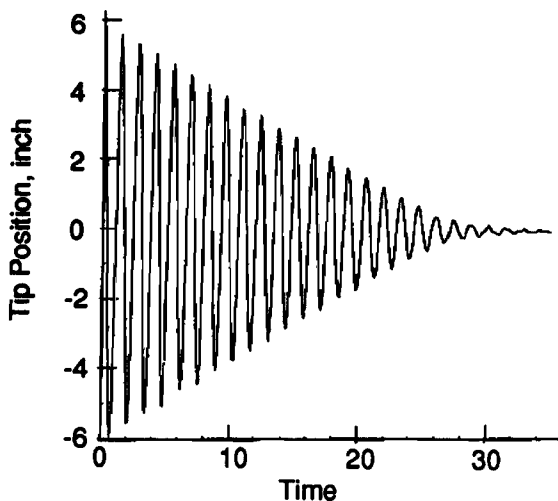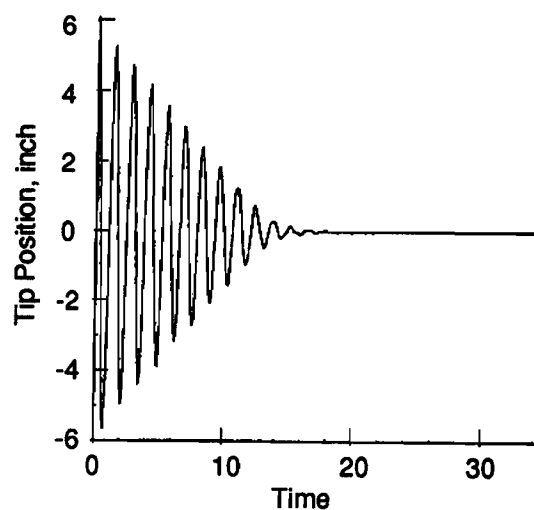


Figure 8. Two Actuator Tip Position Response



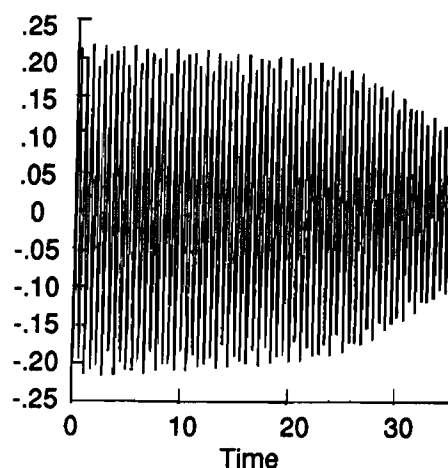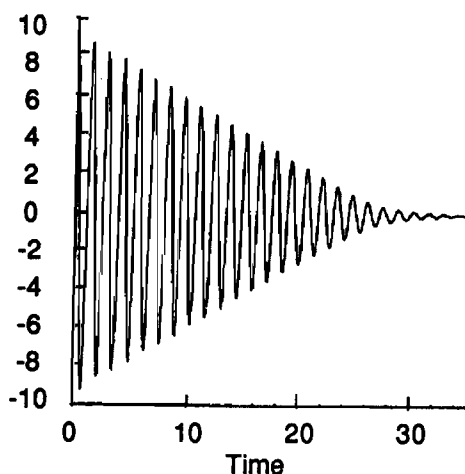Figure 9. Four Actuator Tip Position Response



Figure 10. Flex-Response First Two Modes Two Actuator Model

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# OVERALL DAMPING EFFECTIVENESS

Table 2 summarizes the overall damping effectiveness. Although the transient response has approximately linear decay rate, a viscous damping or exponential decay rate was used to approximate the damping factor for comparison. As shown the active damping was found to be 15 times more effective than no control at all and the simulation model determined that by doubling the actuator authority the effectiveness could be approximately doubled.

| | $\zeta_1^*$ | $T_s$ | Effectivness |
|---|---|---|---|
| Uncontrolled | 0.002 | 420 sec | 1 |
| Passive | 0.003 | 250 sec | 1.5 |
| Active<br>2 NiTiNOL wires | 0.031 | 28 sec | 15 |
| 4 NiTiNOL wires** | 0.054 | 16 sec | 27 |

\* approximated viscous damping
** model prediction

*Table 2. Overall Damping Effectiveness*

## SMA CHARACTERIZATION

Further understanding of how SMA material provides actuation is determined by analyzing the basic parameters that characterize SMA operation. Temperature, displacement and force are all interrelated and are influenced by the power input and the environment. Characterization curves can be used to derive relationships between inputs and outputs. Relationships between parameters can help develop detailed actuator models. These models can better aide the engineer in predicting the performance and defining the limitations of shape memory alloys. The curves shown in figures 11 and 12 show the steady-state power versus temperature and temperature versus displacement curves, respectively. These two curves can be used to derive the steady-state relationship between applied power and displacement. Notice that the path is different in each direction, which is typical of thermal work cycles. These relationships help define nonlinearities; hysteresis and creep. A preliminary investigation of these types of phenomena are just starting to be understood. [7]
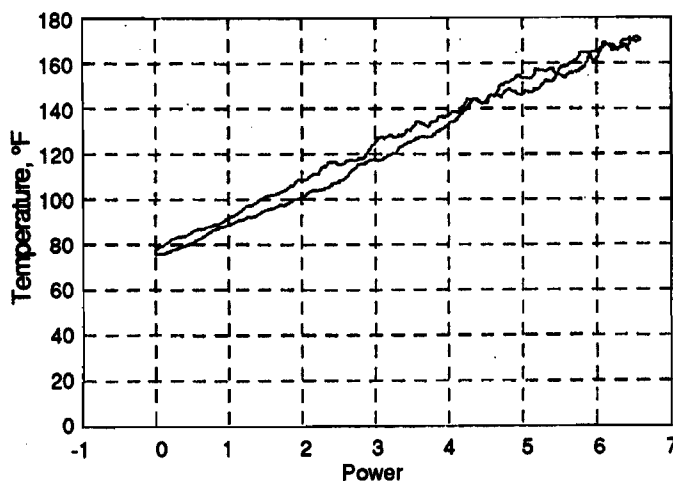
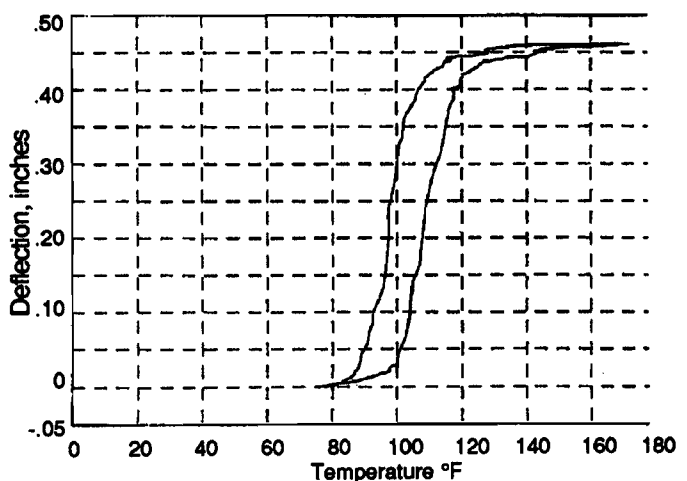*Figure 11. Power vs. Temperature
(Constant Force Test)*

*Figure 12. Temperature vs. Displacement
(Constant Force Test)*

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## SUMMARY

This investigation has verified the feasibility of using shape memory alloy materials as both a sensor and an actuator to actively suppress vibrations of a flexible structure. The overall effectiveness of the active vibration control system was experimentally demonstrated to reduce the spurious vibrations of the flexible structure by a factor of 15. SMA's are an attractive material for use in actuation systems because of their large force capability for a given amount of material, however, they will probably be limited to fairly low frequency applications. Two-way actuation using SMA wires is bandwidth limited by the cooling time of the opposing wire. The SMA sensor showed high resolution along with easy signal manipulation and readily available discrete sensor locations. Finally, SMA characterization will help quantify nonlinearities, hysteresis, and creep to better understand the sensor/actuator functions.

## REFERENCES

[1] Choi, S.B., Thompson, B.S., Gandhi, M.V., "An Experimental Investigation on the Active-Damping Characteristics of a class of Ultra-Advanced Intelligent Composite Materials featuring Electro-Rheological Fluids, Proceeding of Damping 1989, Flight Dynamics Laboratory, AFWAL, Wright-Patterson Air Force Base, Ohio.

[2] Crawley, E.F., and de Luis, Javier, "Use of Piezoelectric Actuators as Elements of Intelligent Structures," Paper 86-0878 at the AIAA/ASME/ASCE/AHS 27th Structures, Structural Dynamics and Materials Conference, San Antonio, TX, May 19-21, 1986.

[3] Wiencko, J.A., Claus, R.O., and Rogers, R.E., "Embedded Optical Fiber Sensors for Intelligent Aerospace Structures," Sensor EXPO proceedings 1987.

[4] Harrold, R.T. and Sanjana, Z.N., "Material Cure and Internal Stresses Monitored via Embedded Acoustic Waveguides," proceeding of ICTTE 86 Technology Shaping our Future, Pittsburgh, PA, Oct 6-8, 1986.

[5] Schetky, L.M., and Perkins, J., "The Quiet Alloys, "Machine Design, Vol. 50, No. 8, April 6, 1978.

[6] Bathe, K.J., Finite Element Procedures in Engineering Analysis, Prentice-Hall, New Jersey, 1982.

[7] Cimino, W.W. and Wilson, D.G., "Working Knowledge for Shape Memory Alloys," Structures Technology, Boeing Aerospace, Kent, Wa, Internal Memo 2-3614-048/89, Feb. 1989.

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