Active vibration and structural acoustic control of shape memory alloy hybrid composites: Experimental results

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Shape memory alloy hybrid composites have been shown both by analytical simulations and experiments to be effective adaptive materials for active vibration and structural acoustics control [Rogers and Robertshaw, *Engineering Science Preprints 25*, ESP25.88027, Society of Engineering Sciences (1988) and ASME Paper 88-WA/DE-9 (1988); Rogers *et al.*, in *Proceedings of the 30th Structures, Structural Dynamics, and Materials Conference,* AIAA Paper 89-1389 (1989)]. Structural acoustics is the study of how elastic structures radiate or receive sound, and in its most fundamental form involves the simultaneous solution of the differential equations describing the structure and fluid media with appropriate boundary conditions between the two, i.e., a "fully" coupled analysis. This paper will review the state-of-the-art of active control utilizing shape memory alloy hybrid composites and present experimental results showing active dynamic tuning by a method called active strain energy tuning (ASET), active control of sound radiation from a clamped-baffled beam, and transient vibration control of a cantilevered beam.

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INTRODUCTION

A. Shape memory alloys

Buehler and Wiley (1965) of the U. S. Naval Ordnance Laboratory received a U. S. patent on a series of engineering allows possessing a unique mechanical (shape)"memory." The generic name of the series of alloys is 55-Nitinol. These alloys have chemical compositions in the range of 53–54 weight percent nickel. A great deal of effort will be expended over the next 10 years in characterizing the material and developing new applications to exploit its remarkable shape memory effect (SME) and its unusual mechanical properties. The Naval Ordnance Laboratory (now known as the Naval Surface Warfare Center) has been very active in characterizing nitinol since its discovery. Several other laboratories made early significant contributions to the understanding of nitinol, in particular the Battelle Memorial Institute and NASA.

The shape memory effect can be described very basically as follows: An object in the low-temperature martensitic condition, when plastically deformed and the external stresses removed, will regain its original (memory) shape when heated. The process, or phenomenon, is the result of a martensitic transformation taking place during heating. Although the exact mechanism by which the shape recovery takes place is a subject of controversy, a great deal has been learned about the unique properties of this class of materials in the past 20 years (Jackson *et al.*, 1972; Schetky, 1979; Wayman and Shimizu, 1972). It appears clear, however, that the process of regaining the original shape is associated with a reverse transformation of the deformed martensitic phase to the higher temperature austenite phase.

Nickel–titanium alloys (nitinol, NiTi) of proper composition exhibit unique mechanical "memory" or restoration force characteristics. The name is derived from Ni (nickel), Ti(titanium), and NOL (Naval Ordnance Laboratory). The shape recovery performance of nitinol is phenomenal. The material can be plastically deformed in its low-temperature martensitic phase and then restored to the original configuration or shape by heating it above the characteristic transition temperature. This unusual behavior is limited to NiTi alloys having near-equiatomic composition. Plastic strains of typically 6%–8% may be completely recovered by heating the material so as to transform it to its austenite phase. Restraining the material from regaining its memory shape can yield stresses of 100 000 ψ (the yield strength of martensitic nitinol is approximately 12 000 ψ) as shown in Figs. 1 and 2 (Cross *et al.*, 1969).

Substantial progress has been made in understanding the nature of the shape memory effect. A great deal of literature has been published over the past 20 years presenting

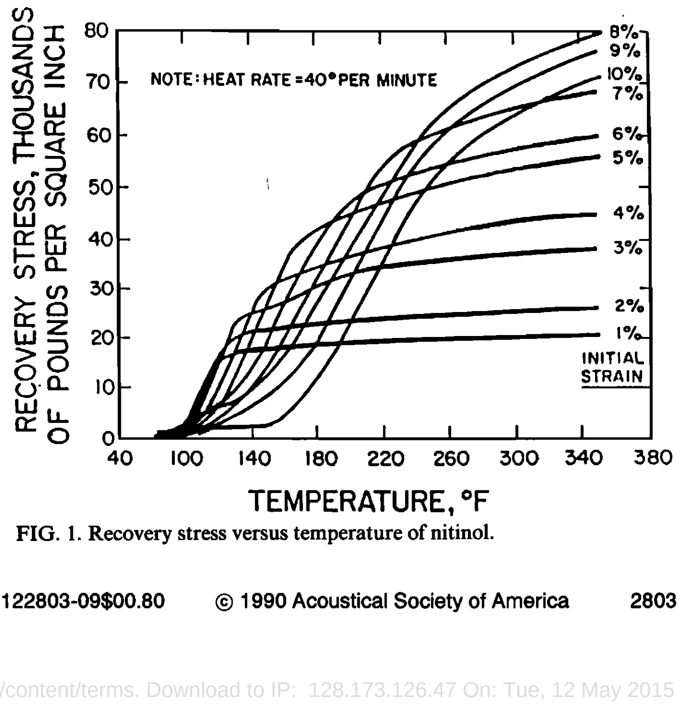

FIG. 1. Recovery stress versus temperature of nitinol.

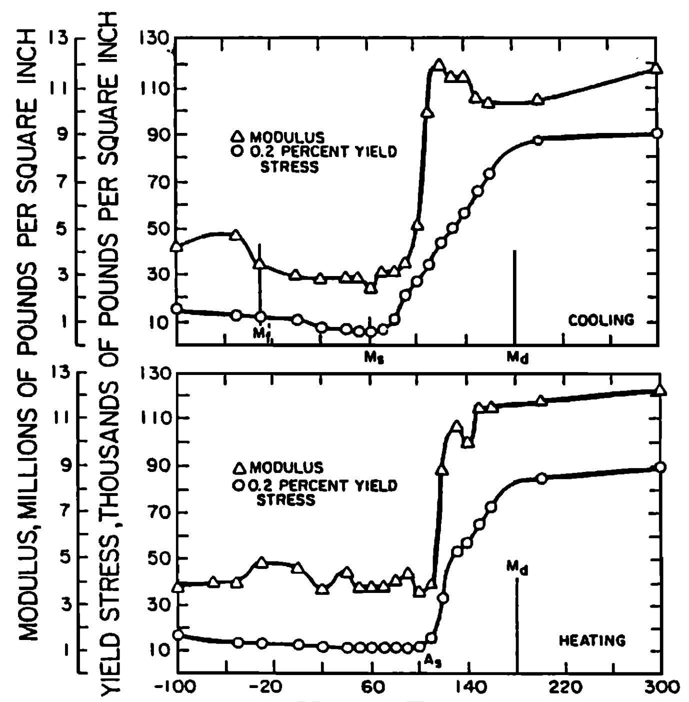

FIG. 2. Young's modulus and yield stress of nitinol versus temperature.

detailed thermal, electrical, magnetic, and mechanical characterizations of this unusual alloy (Goldstein, 1978). An early and complete review was published by Cross *et al.* (1969).

B. Shape memory alloy hybrid composites

The class of the material referred to as SMA hybrid composites in this paper is simply a composite material that contains shape memory alloy fibers (or films) in such a way that the material can be stiffened or controlled by the addition of heat (i.e., apply a current through the fibers) (Rogers and Robertshaw, 1988a,b). Shape memory alloys and the mechanisms by which they exhibit the characteristic SME are explained very briefly below and in greater detail in Liang and Rogers (1990). There is much to be learned about the influence of residual stress and high temperatures on the extent, duration, and repeatability of the SME and dynamic actuator and sensing characteristics of nitinol. The high temperature may be a result of composite fabrication and processing.

Transient and steady-state vibration control can be accomplished with SMA hybrid composites using several techniques. Transient vibration control is defined here as the ability to suppress or damp structural vibration by applying forces (distributed and/or point) to the structure in such a way as to dissipate the energy within the structure. This is accomplished generally by applying point transverse loads to the structure or applying an "actuator film" to the surface of the structure. The approach with SMA-reinforced composites is to simply embed the actuators (shape memory alloys) in the structure such that, when actuated correctly, they exert agonist–antagonist forces off the neutral axis, thereby reducing vibrations (Rogers and Robertshaw, 1988b).

Structural tuning or modification, which may also be used for structural acoustic control, can be accomplished with SMA hybrid composites using a novel technique termed "active property tuning" (Rogers and Robertshaw, 1988b). The modal response of a structure or mechanical component (i.e., plate or beam) can be tuned or modified by simply heating SMA fibers embedded or bonded to a structure in a lamina to change the stiffness of all or portions of the structure. When nitinol is heated to cause the material transformation from the martensitic phase to the austenite phase, the Young's modulus changes by a factor of approximately 4, and the yield strength also increases by a factor of 10. This change in the material properties occurs because of a phase transformation and does not result in any appreciable force and does not need to be initiated by any plastic deformation.

In "active strain energy tuning" (ASET) (Rogers and Robertshaw, 1988b), the shape memory alloy fibers are placed in or on the structure in such a way that, when activated, there are no resulting deflections but instead the structure is placed in a "residual" state of strain. The resulting stored strain energy (tension or compression) changes the energy balance of the structure and modifies the modal response much like tuning a guitar string.

There are several configurations of the composite material that may be used for active strain energy tuning. In both cases, the shape memory alloy fibers are embedded in a material to become an integral part of the material. Before embedding the fibers in the first configuration, the shape memory alloy fibers are plastically elongated and constrained from contracting to their "normal" length upon curing the composite material with high temperature. The fibers are therefore an integral part of the composite material and/or structure. When the fibers are heated, generally by passing a current through the shape memory alloy, the fibers "try" to contract to their "normal" length and therefore generate a large uniformly distributed shear load along the length of the fibers. The shear load then alters the energy balance within the structure and therefore changes its modal response.

Another of the many possible configurations of SMA hybrid composite materials is one in which the shape memory alloy fibers are embedded in a material off of the neutral axis on both sides of the beam in agonist–antagonist pairs. The shear load offset from the neutral axis of the structure will then cause the structure to bend in a known and predictable manner. This technique is well suited for quasistatic shape control and transient (low-frequency) vibration control.

There are numerous other configurations, such as creating "sleeves" within the composite laminate into which the plastically elongated shape memory alloy can be inserted and then clamped to both ends. When the shape memory alloy is heated, the fibers try to contract in the same fashion as explained above. The fibers in a sleeve will exert a concentrated force on the ends of the structure in a direction that is always tangent to the structure at the point where the fibers are clamped to the structure. The difference between the embedded fibers and the fibers in a sleeve is that, in the first case, the force of the shape memory alloy is distributed over the length of the fiber and, in the latter case, the force is concentrated at the end of the structure.

Shape memory alloy hybrid composites have tremendous potential for creating new paradigms for material–structure interaction (Rogers, 1989). The list of scientific areas that can be influenced by novel approaches possible with SMA-reinforce composites is quite large. For example, vibration control can be accomplished by using the distributed force actuator capabilities similar to the common piezoelectric systems. Other approaches to active control are possible with a material that can change its stiffness, physical properties, and apply large distributed loads within a structure, i.e., active strain energy tuning and active property tuning (Liang *et al.*, 1989). Simulation results showing the potential of SMA-reinforced composites to vary the modal response of a composite plate will be presented below.

Applications for SMA hybrid composites extend far beyond vibration control tasks. Active buckling control, or more generically active structural modification schemes, can be imagined in which SMA fibers are stiffened within a composite to alter the critical buckling load of the structure (Rogers *et al.*, 1989). Baz and Tampe (1989) have shown that discrete nitinol actuators can be used to control buckling of flexible structures. SMA composites that are used for various vibration control tasks could also be used for motion or shape control, allowing a structure to maintain a given shape or orientation for an extended period of time. Motion and shape control will in all likelihood involve the simultaneous use of force actuators (SMA) and stiffness actuators (the technique in which the SMA is heated to change its modulus of elasticity) to create a structure that behaves much like a mechanical muscle.

Motion and shape control can be accomplished using the same technique as described above for transient vibration control. The physical, thermal, and controller design will be much more critical than in the transient vibration control scenario. Another possible design approach is to actuate single fibers, with pulse-type signals, much like the all-or-nothing actuation of the individual muscle fibers in the human muscle.

I. EXPERIMENTAL RESULTS

Nitinol hybrid graphite–epoxy beams were fabricated at the Center for Composite Material and Structures Fabrication Center at Virginia Polytechnic Institute and State University. The nitinol fibers have an austenite finish temperature of 100 °F (38°C), a diameter of 0.015 in. (0.38 mm), and were given a 5% strain from the memory shape prior to embedding. Beams with nitinol volume fractions of 5%, 10%, and 15% are fabricated by embedding nitinol fibers on the neutral axis of the beams or balanced symmetrically about the neutral axis. The layup scheme for 15% nitinol volume fraction is shown in Fig. 3. Similar schemes are used for the 5% and 10% nitinol volume fractions with the only difference being the number of embedded nitinol fibers. A 5% nitinol volume fraction beam is fabricated by embedding only 8 nitinol fibers and the 10% and 15% volume fraction beams contain 16 and 24 fibers, respectively.

Specifications

Graphite epoxy:	5245 prepreg system	
Dimensions:	Length (L)	= 32.25 in (81.92 cm)
	Width (W)	= 0.860 in (2.18 cm)
	Spacing (S)	= 0.031 in (0.79 mm)
	Thickness	= 0.034 in (0.86 mm)
No. of actuators		= 24 x .015 in dia
Nitinol volume fraction		= 15%

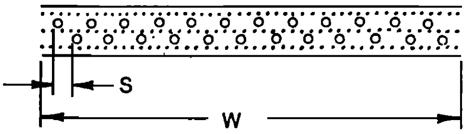

FIG. 3. Layup scheme for the nitinol hybrid composite beam.

A special tool plate was designed (Barker, 1989) to constrain the nitinol fibers from returning to their memory shape during the high temperatures of the composite cure cycle. Graphite epoxy prepreg (5245 C carbon fiber prepreg system) and strained nitinol fibers are laid on the tool plate using the layup scheme explained above.

The cured composite beam is removed from the tool plate and clamped at both ends in the test fixture so that the transverse vibrations occur out of the gravitational field. Screws are used to clamp the embedded nitinol fiber to the test fixture if desired. A thermocouple (Omega, E-type, chromel-constantan thermocouple) is located on the surface of the beam to allow the nitinol-reinforced composite to be tuned to a specific temperature. The nitinol fibers are activated by applying an electric current through the beam. Heating therefore occurs as a result of the electrical resistance of the nitinol fibers. A constant current power supply (HP-6268B programmable dc power supply) is controlled manually to bring the temperature of the beam to the desired temperature. An electromagnetic displacement transducer (Electro Corporation, Electro-Mike EMDT 85003) is used to sense the dynamic response of the composite beam. A PC-AT computer and A/D board (Data Translation, Inc., DT2801 A/D board) are used to store temperature and displacement measurements. The experimental apparatus is shown in Fig. 4.

Three terms are used to describe the state of the beam prior to the test performed. "Original" refers to a beam that has never been heated or "activated." Testing of an original beam therefore refers to the first time the beam is activated after being clamped at both ends in the test fixture. The term "rested" refers to a beam that has been allowed to rest at room temperature for the length of time necessary to relieve residual stresses as a result of thermal expansion of the graphite–epoxy matrix incurred during the activation process. The term "worked" refers to a beam that has not been rested for the necessary length of time to relieve the residual stresses incurred during the activation process.

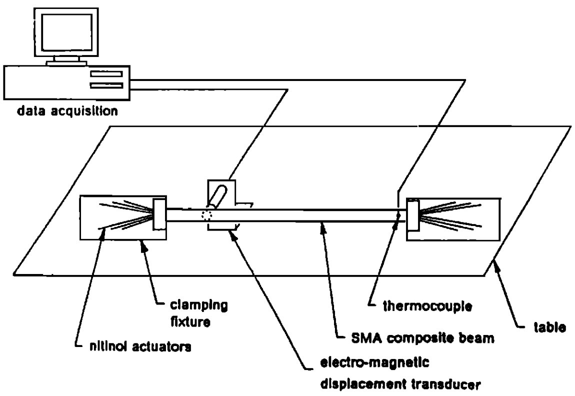

FIG. 4. Experimental apparatus for active strain energy tuning.

Natural frequency versus temperature testing is performed by determining the first three natural frequency modes at different temperatures between room temperature and 300 °F (149 °C). The maximum continuous service temperature of the graphite–epoxy matrix (5245C carbon fiber prepreg system) is 300 °F (149 °C). Short term service is rated at 400 °F (204 °C). Because of the large recovery stresses of embedded nitinol fibers, the maximum temperature of the natural frequency versus temperature testing is limited to 300 °F (149 °C) to prevent any permanent change in the dynamic behavior of the beams and the test fixture or constraints. The beam is heated to the desired temperature by manually increasing the magnitude of the current through the nitinol fibers. When the desired steady-state temperature is reached, vibrations are induced in the clamped beam. Data are sampled in real time and an FFT is performed on the discrete data points to extract the resonant frequencies of the vibrating beam. Three data sets are taken at each temperature and the resulting FFTs are averaged. The temperature is measured after each data set is sampled. Three averages are taken in this fashion to verify that steady-state temperature is achieved.

The natural frequencies versus temperature of a rested nitinol-reinforced beam having 15% nitinol volume fraction are shown in Fig. 5. A least-squared polynomial-curve-fitting procedure is performed on the experimental data points using the least-squares method and is shown with experimental data. Nitinol fibers extending outside each end of the clamped–clamped beam are not constrained. This allows the nitinol fibers to contract to some degree within the matrix material. The nitinol fibers are able to cause a strain within the matrix material, and recovery stress of the nitinol fibers is balanced within the matrix material as well as the clamped boundary. Some portion of the recovery stress is applied to the matrix and the remainder is applied to the boundary. The first natural frequency increases from 21 Hz at room temperature to 62 Hz at 300 °F (149 °C). ASET yields a change of nearly 200% in the first natural frequency for the 15% nitinol volume fraction beam. The change in frequencies occurs over a large temperature range—approximately 70 °F (21 °C) to 250 °F (121 °C). This range is very linear up to 200 °F (93 °C).

The natural frequency versus temperature of a graphite–epoxy beam without embedded nitinol fibers was also determined. The results for the first natural frequency are shown in Fig. 6. As expected, the natural frequency decreases as a function of temperature as a result of both a decrease in stiffness and thermal expansion of the graphite–epoxy matrix. Buckling is apparent as the beam approaches 300 °F (149 °C). This indicates that thermal expansion and the corresponding compressive load play an important role in the change in decreasing the natural frequencies of the graphite-epoxy beam. Considering ASET, one would expect the thermal expansion of the matrix material to have a cancelling effect on the tensile recovery stress of the embedded nitinol fibers. This means that even larger increases in the natural frequencies can be achieved if SMA composites are

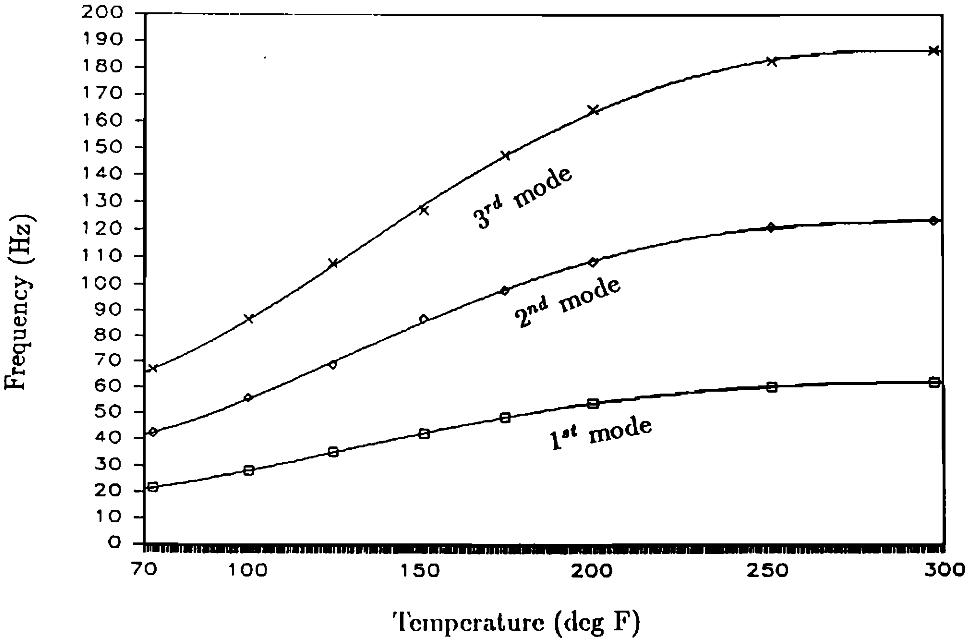

FIG. 5. ASET of "rested" SMA hybrid beams with free fibers, 15% nitinol volume fraction.

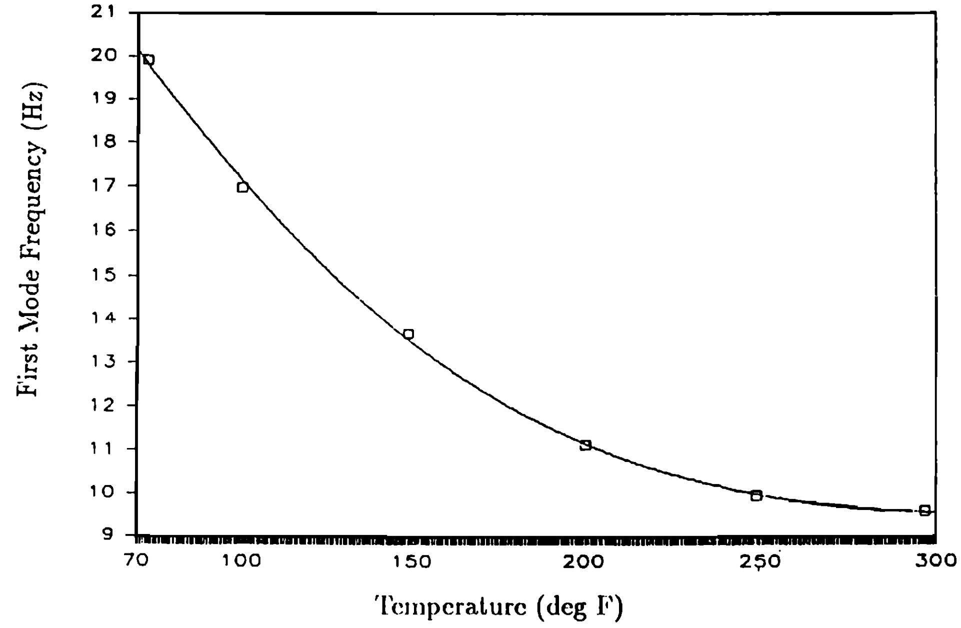

FIG. 6. Natural frequency versus temperature at a clamped–clamped graphite-epoxy beam.

tailored to have a small coefficient of thermal expansion in the direction of the embedded nitinol fibers.

The first natural frequency versus temperature for the graphite-epoxy beam (without embedded fibers) is compared to the rested 15% nitinol volume fraction beam in Fig. 7. Both beams have similar first natural frequencies at room temperature. As the beams are heated, the graphite-epoxy beam shows a decreasing frequency as a function of increasing temperature. The graphite-epoxy beam has a first natural frequency of 10 Hz at 300 °F (149 °C). The rested 15% volume fraction beam, on the other hand, has an increasing frequency as a function of increasing temperature. The rested 15% volume fraction beam has a first natural frequency of 62 Hz at 300 °F (149 °C). This figure demonstrates that, by including embedded nitinol fibers, the activated first natural frequency of a clamped-clamped beam at 300 °F (149 °C) can be changed by 520%. It is apparent from these results that an SMA composite structure may be tailored to give a uniform dynamic response over a large temperature range or give some other desired dynamic response as a function of temperature.

A. Structural acoustic control of SMA hybrid composite beams

Active control of sound radiation from a clamped, baffled composite beam with embedded nitinol fibers with demonstrated using two different control strategies by Saunders *et al.* (1990). The unique behavior of the SMA hybrid composites was utilized to allow minimization of radiated sound for harmonic beam vibration and placement of the peak radi-

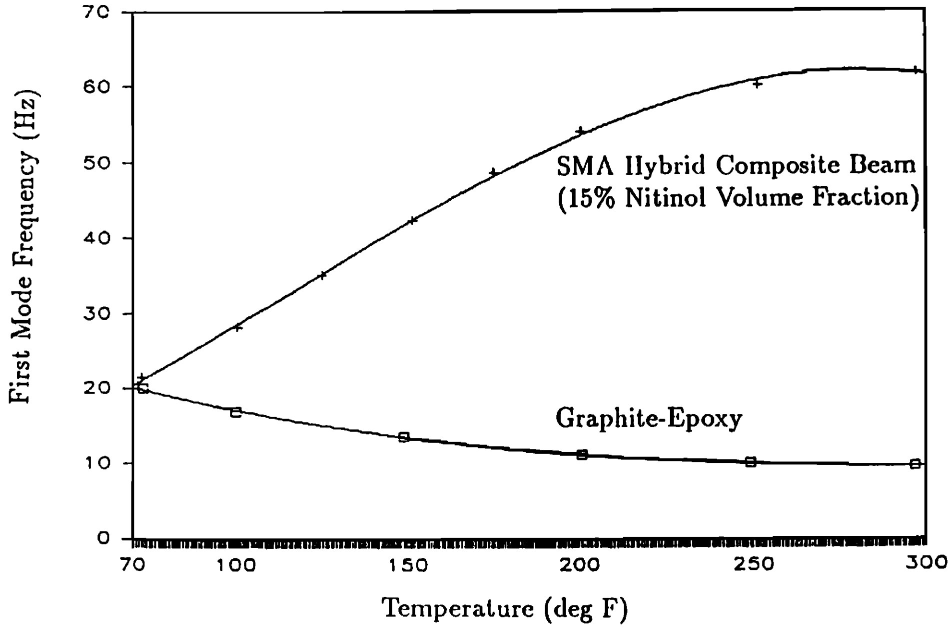

FIG. 7. Comparison of SMA hybrid beam and graphite-epoxy beam first free mode with respect to temperature.

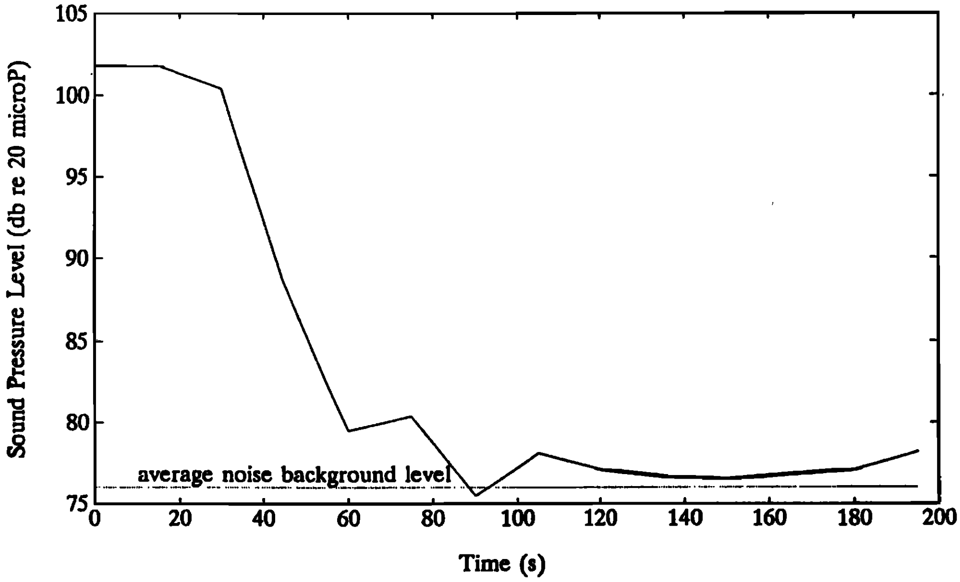

FIG. 8. Controlled sound pressure ($f_0 = 35$ Hz).

ation response at specified frequencies within a controllable range. The minimization control, based on gradient search techniques, was effective in reducing the measured sound pressure to the background noise levels. Peak radiation frequency placement control, derived using a first-order thermal model, allowed tuning of the beam radiation response anywhere within an octave bandwidth above the fundamental mode.

A nitinol-reinforced graphite–epoxy beam, 32 in. (0.822 m) long, 0.80 in. (2.03 cm) wide, and 0.040 in. (0.1 mm) thick, was made with 15% nitinol volume fraction. The beam was clamped on each end into a special mounting structure providing vibration out of the gravitational field. A Plexiglas baffle was constructed to enhance the subsonic radiation field. Excitation of the beam was provided by a nonintrusive magnetic shaker.

Digital control of the composite beam was implemented on an AT style computer using two commercially available data acquisition plug-in boards to perform A/D and D/A operations. An Hp 6268B dc power supply, digitally controlled, was used for resistive heating of the nitinol wires. Exact configuration of the experimental setup depended on the experimental objective. Details of the sound minimization experiment and the peak radiation placement experiment are given below.

A closed-loop control system was implemented to shift beam resonances away from discrete, harmonic, disturbance frequencies. The control method used feedback from a microphone to modify the composite beam natural frequencies via ASET. A brief discussion of the minimization algorithm used for the controller is provided along with a description of the experimental procedure and results.

The minimization control experiment used a constrained search technique suggested by Hooke and Jeeves (1961). The Hooke and Jeeves (or pattern) search is categorized as a direct, multidimensional search method under the myriad of optimization routines available. For this application, it was actually a one-dimensional search, i.e., the minimum sound-pressure level was determined as a function of beam resonant frequencies only. Minimization of beam radiated noise was performed at various disturbance frequencies. The controller minimized sound-pressure levels for frequencies as high as the eighth vibration mode of the beam (324 Hz). The disturbance frequencies used in the experiments were chosen to coincide with beam resonant frequencies. Results for two minimization experiments are presented next.

Figure 8 shows the time history of the sound-pressure level for minimization control applied to a sine disturbance at 35 Hz ($n = 1$ mode). Controlled sound-pressure levels showed a reduction of 20–25 dB. The initial step size was 2 V with a 15-s sample period. The control input for this experiment went directly to the highest possible input value mentioned earlier because there was no other resonance below the fundamental mode to pass through the excitation frequency. Thus Fig. 8 simply shows the effect of the 35-Hz resonance moving away from the excitation frequency.

The second minimization experiment was for excitation at 145 Hz ($n = 4$ mode). Sound-pressure levels during the minimization are shown in Fig. 9. The magnitude of the sound reductions was about 25–30 dB. Again, step size was 2 V with a 15-s sample period. For this case, the time history of the sound pressure showed the effect of the third vibration mode moving close to the excitation frequency. This is evident in the rising sound-pressure level beginning at 40 s on the plot. The controller then adapted the control input to modify the beam so that the disturbance was located at the minimum between the third and fourth vibration modes.

The results discussed above show the validity of using SMA hybrid composites, in conjunction with a control algorithm, to minimize subsonic structural acoustic radiation from a clamped beam. Additional minimization control experiments were completed at different modal frequencies using various combinations of step size and sample period.

B. Nitinol fiber sensors

Nickle–titanium shape memory alloys have many peculiar properties, many of which can be exploited for actuation

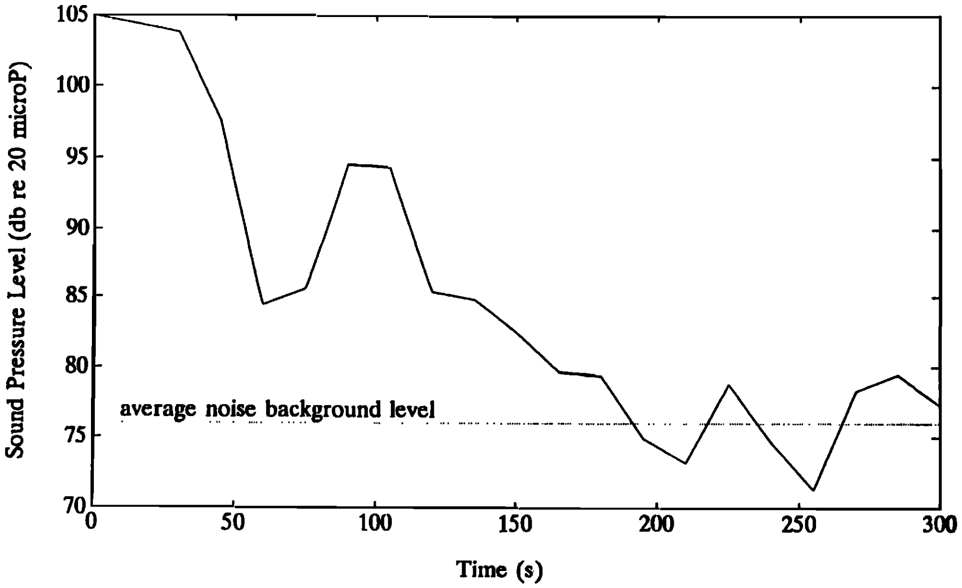

FIG. 9. Controlled sound pressure ($f_0 = 145$ Hz).

or sensing applications. As is the case with many actuator materials, such as piezoceramics and PVDF, nitinol can be used to perform sensing as well as actuation. Nitinol strain sensors, however, differ from nitinol actuators in that the sensors generally utilize only the psuedoelastic "phase," whereas nitinol actuators utilize the reversible transformation between the martensitic and austenite phase. The distributed (or integrated) nitinol sensors currently being utilized measure strain. The utility of the integrated strain information for structural acoustic control applications has been discussed in many references related to optical fiber sensors (Cox *et al.*, 1989) and in a review paper by Fuller *et al.* (1989).

The nitinol fiber strain sensors are simply superelastic nitinol wires. The basic concept is to measure the change in resistance of the nitinol as a function of integrated strain. This concept allows for very simple processing as the nitinol sensor is nothing more than an unbalanced arm in a Wheatstone bridge. Nitinol has a high resistivity for a metal, making it well suited for strain sensing. The superelastic nature of the nitinol also means that strains up to 6% can be reliably and repeatedly measured.

Experimental demonstration of the nitinol sensor was performed by embedding a 0.012-in. (3-mm)-diam fiber in a fiberglass cantilever beam off the neutral axis. The nitinol sensor was then used as the active leg of a Wheatstone

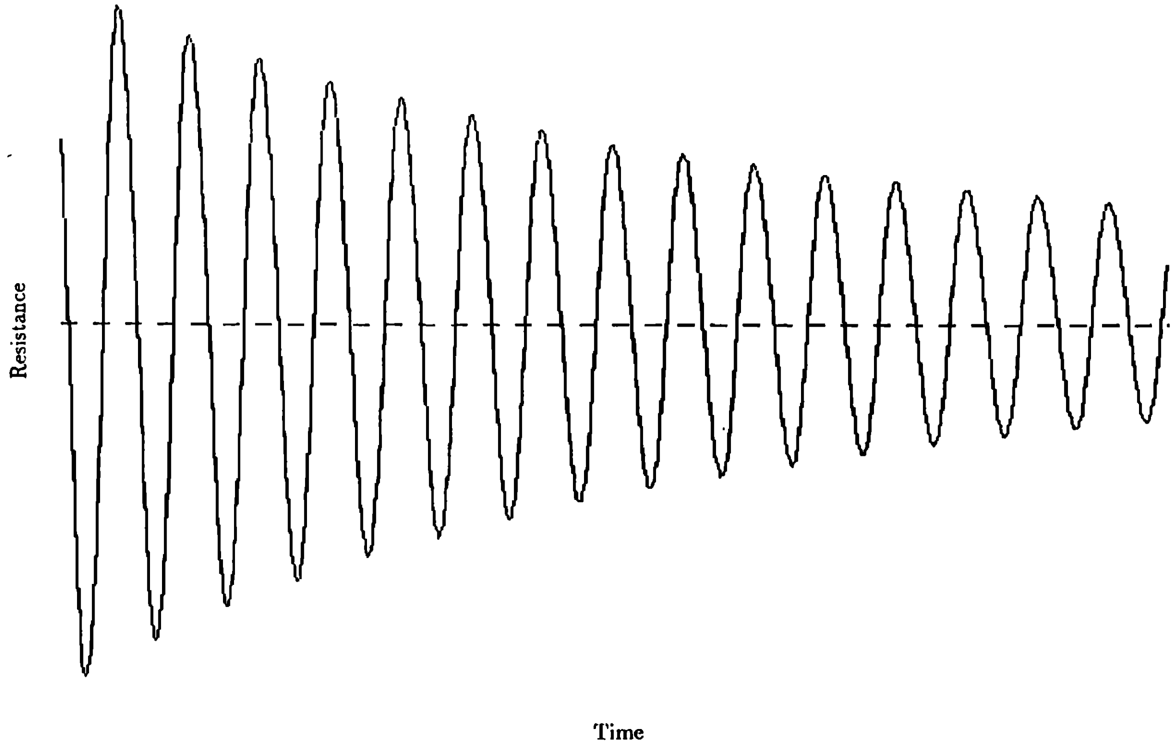

FIG. 10. Response of a pseudoelastic nitinol strain sensor in a freely vibrating cantilever beam.

bridge. When the embedded nitinol fiber is strained, the resistance increases and the bridge is no longer balanced, resulting in a voltage across the bridge. The cantilever beam was used to verify the integrated strain capabilities of the fiber in both static and dynamic modes. Static and dynamic tests show a linear response for root strains (of the fiber) up to 1.2%, the maximum strain tested with the beam. Calibration tests of the nitinol fiber itself has indicated a linear response greater than 6% strain. However, once the sensing fiber has been strained beyond 6%, it becomes plastically deformed. The experimental response of the embedded nitinol fiber to a freely vibrating cantilever beam with a first mode of approximately 4 Hz is shown in Fig. 10. The primary advantages of nitinol strain gauges are their ease of implementation and large range. Current work involves using the nitinol fiber as a dual-mode sensor, i.e., to measure temperature and strain simultaneously.

C. Transient vibration control

The reversible strain recovery behavior of nitinol provides an opportunity to impart cyclic loads on a structure for transient vibration control. In this application, the nitinol is heated resistively and then cooled either passively or actively by forced convection or conduction using thermoelectric coolers. An experimental study was performed to determine the control power, authority, and frequency response for a specific actuator design using nitinol wire approximately 0.005 in. (0.127 mm) in diameter and passive cooling.

The experimental apparatus shown in Fig. 11 consists of a 2-ft cantilever beam. The beam cross section is 0.040 in. (1 mm) thick and 2 in. (5 cm) high with the first two bending modes at 3.1 and 20.7 Hz. The beam is clamped to the base so as to allow the free bending vibration to occur out of the gravitational field. The control forces, or moments, are exerted on the beam by 0.005-in. (1.25-mm)-diam wire attached to the beam 3 in. (7.5 cm) from the clamped end. There are two such actuator "patches," one in either side of the beam. Each patch consists of one 24.6-in. (62.5-cm) nitinol wire that is "threaded" back and forth from the clamping fixture (the root of the beam) to the beam attachment point 3 in. (7.5 cm) from the root. Threading the actuator in this fashion created eight effective 3-in. (7.5-cm)-long actuators on each side of the beam. The actuators were anchored to the beam and the base by connectors made of bakelite. The insulating and elastic characteristics of the bakelite provide for simple electrical heating through two terminals on the base which doubled as end restraints for the laced nitinol actuators. Each patch was independently controlled by a voltage gain programmable direct current amplifier. The amplifiers were controlled by a PC-AT with D/A and A/D hardware.

The control law used was simple displacement velocity feedback. It was also determined that the displacement gain was very small and could be eliminated to simplify the controller software and instrumentation requirements. The velocity of the beam was calculated from two strain gauges mounted on the beam as indicated in Fig. 11. A deadband was included in the control law to account for the bang-bang-type control. It is well know that pulse width modulation (PWM) is a more efficient and effective method of control for nitinol actuators. Future studies will address these issues.

The nitinol volume of the two actuators was 9.28×10^{-4} in.^{3} (1.52×10^{-2} cm^3). The first bending mode excited by various initial conditions was controlled. During this control, some second mode vibration could be observed as a result of the impulsive lateral forces being imparted by the actuators. The second and higher modes exhibited high rates of damping. Fig. 12 shows the free vibration response and the closed-loop control response of the first bending mode of approximately 3 Hz. The logarithmic decrement was increased from 0.04 for the uncontrolled beam to 0.2.

II. CONCLUSIONS

A number of experimental studies that demonstrated the dynamic behavior and control of vibration and structurally radiated noise were presented. Active strain energy tuning was shown to be a viable control technique for a number

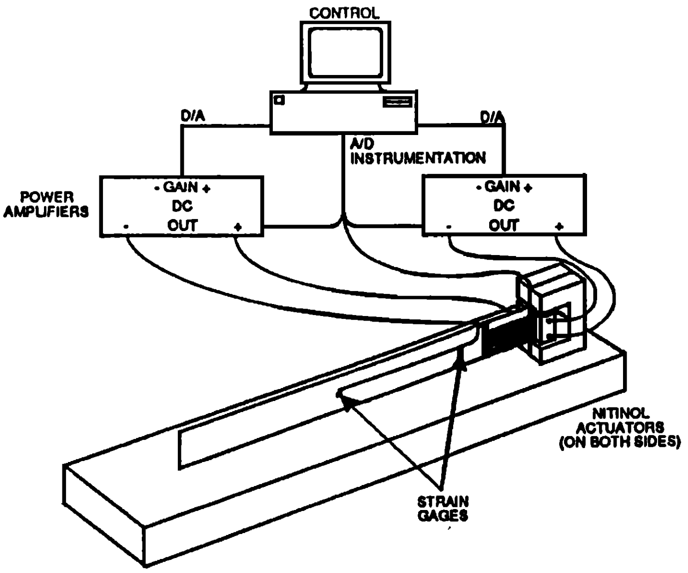

FIG. 11. Transient vibration control experiment.

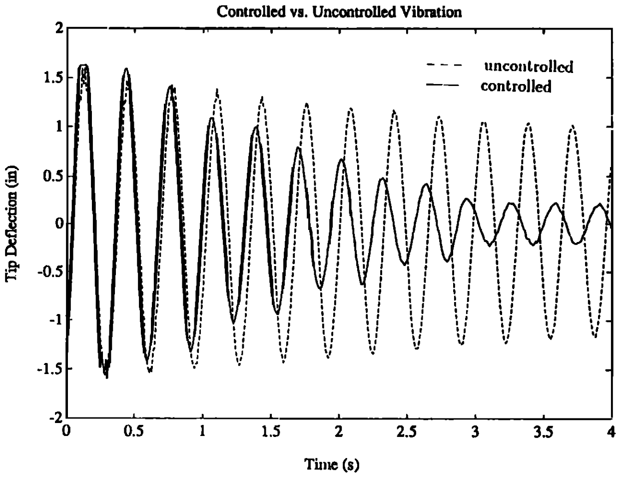

FIG. 12. Controlled versus uncontrolled vibration of a cantilever beam.

of diverse applications: Modifying the dynamic response of composites or creating variable-stiffness materials; design composite structures with a uniform dynamic response over a wide temperature range; and control of subsonic, structural-acoustic radiation.

The shape memory alloy, nitinol, was also demonstrated as a distributed (integrated) strain sensor and a transient vibration actuator. Even though there are numerous identified problems with SMA hybrid composites that have yet to be investigated and understood for active control applications, it has shown great potential and versatility.

ACKNOWLEDGMENTS

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