VIBRATION AND SHAPE CONTROL OF SMART STRUCTURES

Pei-Zon Huang+
Shih-Ming Yang++
Institute of Aeronautics and Astronautics
National Cheng Kung University
Taiwan, China

Abstract

The stringent design requirement of aerospace systems has called for the needs of smart structures, structure systems with built-in sensor and actuator that can actively change their physical geometry and property to adapt to the working environment. This paper presents the smart structure design with built-in piezoelectric sensor/actuator and controller for dither excitation, vibration suppression, and shape control. Two smart structure specimens, an aluminum beam with surface bonded piezoelectric sensor/actuator and a glass fiber composite laminated beam with embedded piezoelectric sensor/actuator, are fabricated and tested. Three control circuits driven by one 9VDC battery instead of the expensive and heavy power supply, wave form synthesizer, and power amplifier required in laboratory, are also developed. It is shown experimentally that the smart structure technology of integrated sensor, actuator, and controller is effective both in vibration control and shape control. Development of aeroservoelastic aircraft systems will be becoming a reality.

Introduction

The stringent design requirement of aerospace systems has created the need for smart structure, structures with built-in piezoelectric sensor/actuator that can actively change its physical geometry and/or property to adapt to the working environment. Recent studies on structural control systems by using piezoelectric materials have been shown to be effective in vibration suppression of beam, plate, and shell structures. Piezoelectric sensor can generate an electrical charge in response to the applied mechanical strain; conversely, piezoelectric actuator provides a mechanical strain subject to the applied electric field. Their advantages in sensor/actuator applications include: no magnetic field generated in the conversion of electrical energy to mechanical motion, hence no electric-magnetic interference or electric-magnetic compatibility problem, fast response time within 1 msec, and high resolution in mechanical positioning within micron. Surface bonded piezoelectric element are commonly used in structures of isotropic materials(1) while it is also possible to embed piezoelectric materials in composite laminated structures(2). The adaptive nature to external stimuli makes them the best candidate in vibration and shape control application of aerospace systems.

Mathematical models of piezoelectric materials have been available in the literature. The associated analytical solutions, however, are restricted to relatively simple geometry and boundary conditions. And most were emphasized on either analytical or numerical results. Report of hardware implementation on composite smart structures is very limited. Crawley and deLuis(1) were among the first to embed the piezoelectric elements in composite cantilever beams, but the natural frequency, mode shape, and damping ratio were not reported. Bronowicki et al.(3) fabricated a composite structure with embedded piezoelectric sensor and actuator, but they presented only the vibration control simulation results. The manufacturing technique for composite structures with embedded piezoelectric elements was also developed

+Undergraduate student
++Correspondence addressee: Professor, Institute of Aeronautics and Astronautics, National Cheng Kung University, Taiwan, R. O. C.
Tel:+886-6-2389122
Fax:+886-6-2389940
email: smy@mail.iaa.ncku.edu.tw

by Yang and Chiu(2), and the vibration control study of a $[0/90]_{6S}$ composite laminated plate was conducted by Yang and Bian(4).

However, most of the smart structure experiments reported were conducted on laboratory environment. Many instruments, including power supply, wave-form synthesizer, and power amplifier, would be required to generate and to monitor the piezoelectric effects, but these instruments are usually heavy, expensive, and may not be applicable for in-situ operations. This paper presents a smart structure design by using piezoelectric sensor/actuator combined with a control circuit of relative simple drive electronics for the vibration and shape control of aerospace systems. Three control circuits, one for dither excitation, the other for vibration suppression, and the third for shape control, are developed. The controller are driven by one 9VDC battery instead of the expensive and heavy instruments required in laboratory. In addition, two smart structure specimens, an aluminum beam with surface bonded piezoelectric sensor/actuator and a glass fiber composite laminated beam with embedded piezoelectric sensor/actuator, are fabricated and tested. Experimental results show that the smart structure technology of integrated sensor, actuator, and controller is effective both in vibration control and shape control.

Dynamics of Smart Structure

Two smart structure specimens, an aluminum beam with surface bonded piezoelectric sensor/actuator and a glass fiber composite laminates with embedded piezoelectric sensor/actuator, are considered in this paper. In the first specimen, a pair of piezoelectric sensor/actuator (PZT) of 120 × 30 × 0.39 mm is adhered to the top and bottom surfaces and near the root of a cantilever beam of 400 × 30 × 1.2 mm as shown in Figure 1. The bonding technique is developed by matching the surface condition, epoxy properties, and insulation condition at the interfaces. Because piezoelectric material is a strain-induced actuator, it is therefore advisable to place it as closer to the cantilever end as possible.

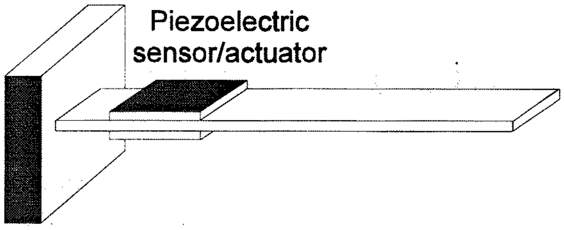

Figure 1. Geometry of a flexible beam with surface bonded sensor/actuator.

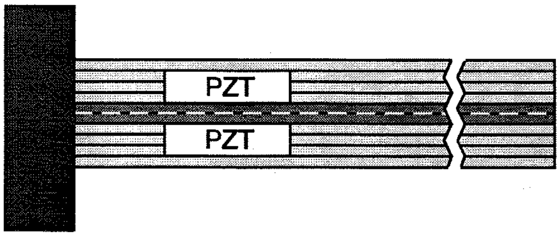

Figure 2. Smart structure cross section of embedded piezoelectric sensor/actuator.

The manufacturing techniques of composite laminated structure with embedded piezoelectric elements has previously been developed(4). Care has to be taken in keeping the electrical insulation while preventing the piezoelectric elements from cracking in the curing process. Figure 2 shows the 270 × 40 × 1.3 mm composite laminated beam of stacking sequence $[90/90/90/90/0]_S$ embedded with a pair of piezoelectric sensor/actuator of 120 × 30 × 0.39 mm, each about the thickness of three laminate layers. In order to encapsulate the sensor and actuator, the corresponding pre-prag tapes are processed to have a square cut-out. One electrical lead is attached to the center of the top and bottom surfaces of each piezoelectric element; no conductive epoxy is required for attaching the lead. The electrical leads (M-line accessories 326-DFV) are led through the adjacent layers to the edge of the cantilever end. Each lead goes through a needle (24G-1, $25 \times 0.55\phi$ mm) at the cantilever end to prevent the electrical lead from being brittle during and after the curing process. The composite smart structure is then vacuum bagged, hot pressed, and cured at about 171°C. Previous work by Crawley and deLuis(1) showed that the ultimate strength of the specimen with or without the embedded piezoelectric element can vary as mush as 20%. In a similar work, Yang and Chiu(2) also showed from the tensile test of two specimens that the elastic modulus of the structure with embedded piezoelectric element is about 50% lower than that without any embedding. But these static test results are heavily influenced by the volume (size) effect. In their coupon tests, the volume

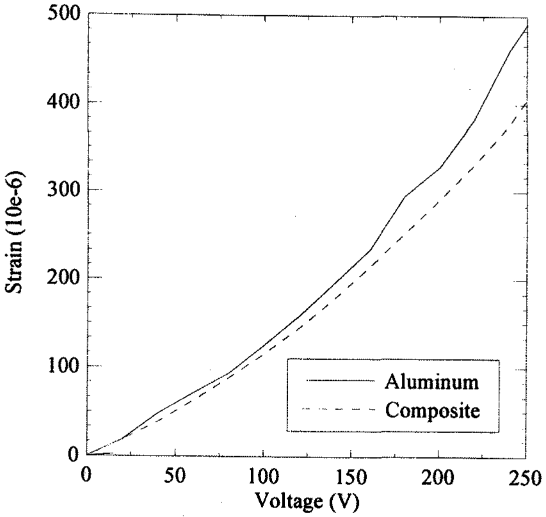

Figure 3. Static test results of strain and applied voltage.

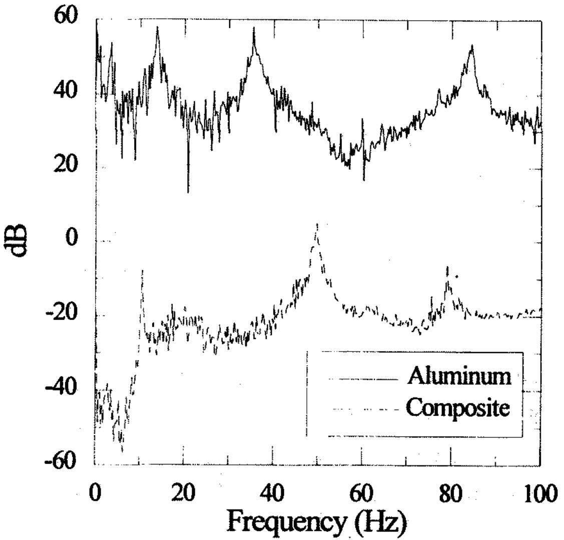

Figure 4. Frequency response function of modal testing.

ratio between the piezoelectric element and composite laminates is about 15%. Whereas in this study the inertia and stiffness of the piezoelectric element is negligible for the relatively small volume ratio.

The smart structure specimens are also tested for their piezoelectric effectiveness by adhering a strain gauge adjacent to one of the piezoelectric elements. The piezoelectric element driven by DC voltage from a power supply (HP6035A) serves as actuator, while the strain gauge measures the mechanical strain signal under direct piezoelectric effect. Figure 3 shows the piezoelectric effectiveness of the beam structures in which the mechanical strain increases in a rather linear relation from 0 to 250 VDC. The static test results indicate that the piezoelectric effectiveness can be maintained when surface bonded on the aluminum beam or embedded inside the composite laminated structure. A prerequisite of effective control application is to understand the system dynamics. For the application of dither excitation, it is necessary to identify the natural frequencies of the smart structure in order to increase the operational sensitivity. Modal testing is then conducted to measure the nature frequencies of both specimens. The modal parameters are obtained by measuring the input/output transfer function of the piezoelectric sensor/actuator through a spectrum analyzer (HP3567) as shown in Figure 4. The first three vibration modes are at 3.5, 13.75, and 35.5 Hz for the aluminum beam, and at 10.5, 49.75, and 79.0 Hz for the composite structure.

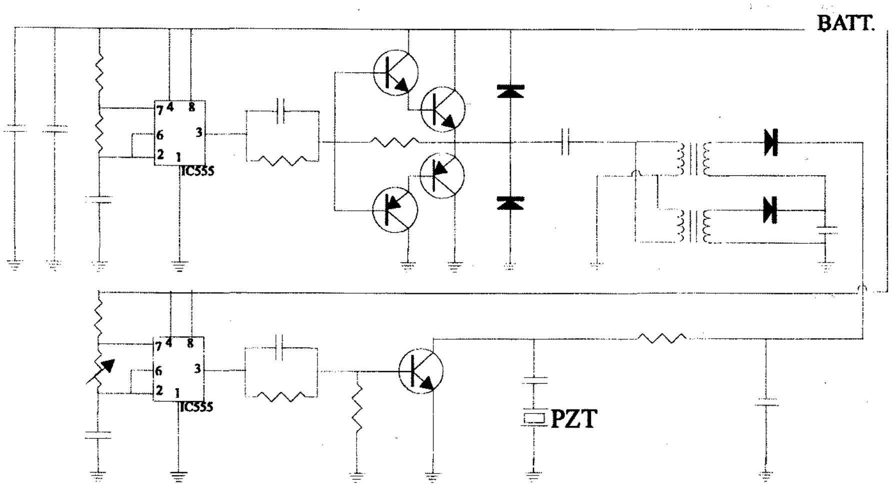

Figure 5. Schematic diagram of the dither excitation control circuit.

Control Circuit Design

1. Dither excitation

One of the major requirement for aircraft on-board implementation is to have least intrusive to aircraft design in terms of weight, power, and reliability. For better actuator performance per watt and miniaturization of the controller, a control circuit is developed to provide effective control input to the actuator as well as reliable signal output from the sensor. Figure 5 shows the schematic diagram of the dither excitation control circuit which is composed mainly by power amplifier, wave-form synthesizer, and signal conditioning. The power source from the 9 VDC battery is amplified by a factor of 8 to 10 by the oscillating current using IC555. It is then transformed into an AC driving source to the piezoelectric actuator for dither motion control. One would prefer a harmonics signal for best dither excitation performance, however, it is very power-consuming in the conversion of a DC signal to an AC square-wave signal and then to the desired AC sine-wave signal. This process not only reduces the output power voltage, but also makes the electronic components vulnerable to burn-down. The output wave-form of this circuit is therefore selected between an AC square-wave and a sine-wave, and the output frequency is tunable thereby being adaptable to structures of different natural frequency. Figure 6 shows the dither motion of the cantilever aluminum beam, where the peak-to-peak tip displacement can be as high as 35 mm. Similarly for the composite structure, the tip displacement is as high as 15 mm. Because of the dynamic range of the piezoelectric actuator, any required dither frequency within the control bandwidth can be achieved. Such dithering motion at suitable frequency is applicable to advanced aircraft systems with active wing design.

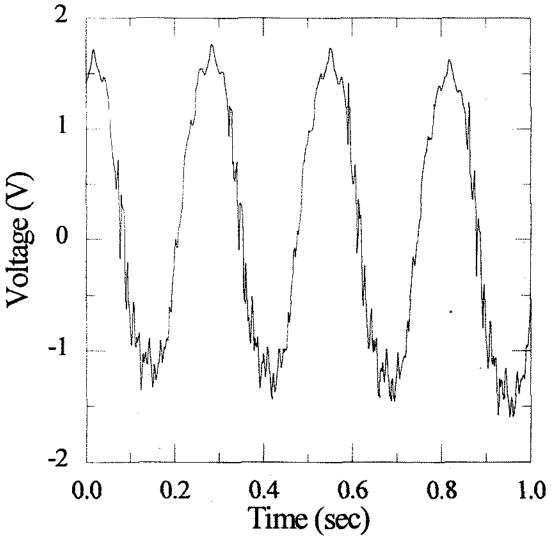

Figure 6. Tip response excited by embedded piezoelectric actuator at 75V.

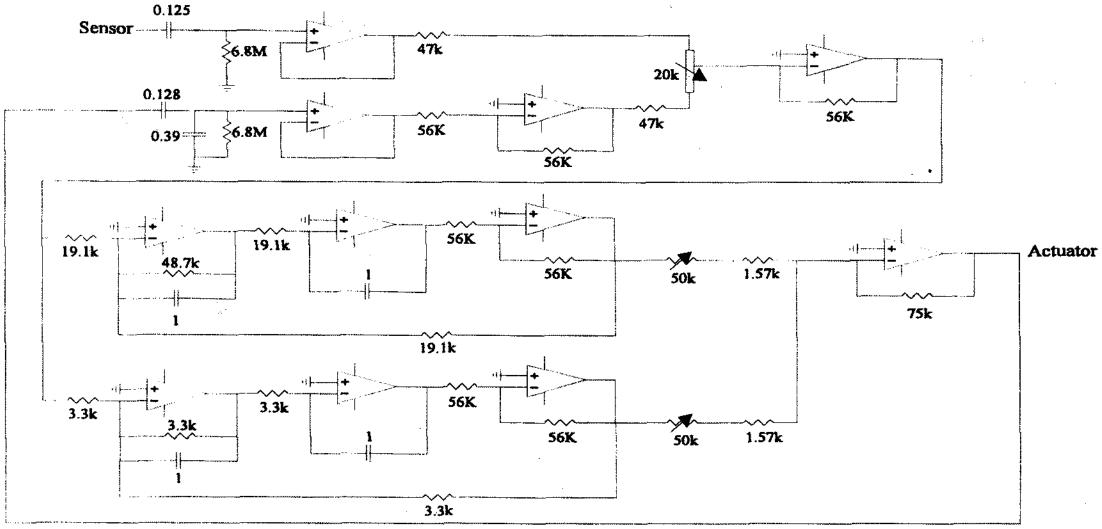

Figure 7. Schematic diagram of the vibration suppression circuit.

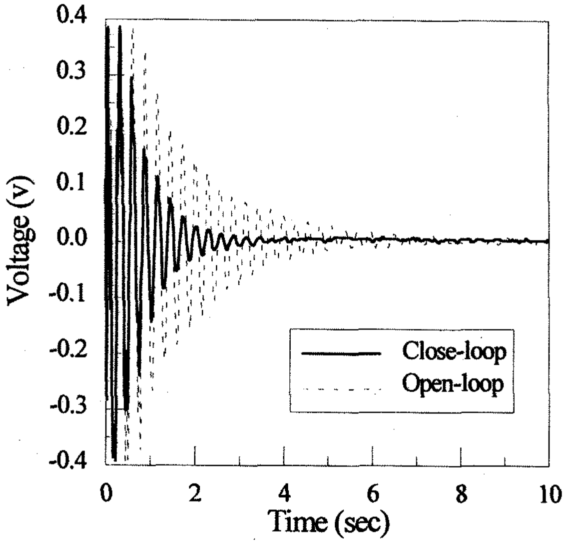

Figure 8. Piezoelectric sensor of the aluminum beam in open-loop and close-loop system.

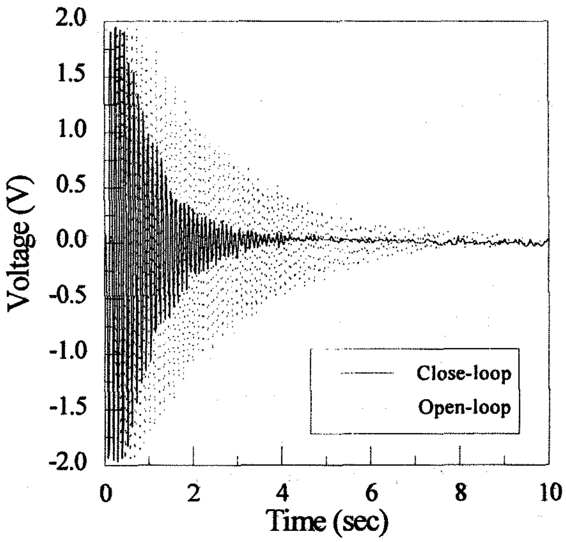

Figure 9. Piezoelectric sensor of the composite beam in open-loop and close-loop system.

2. Vibration suppression

It has been shown that velocity feedback can increase the structural damping if sensor and actuator are collocated(5). The objective is to provide the smart structure with built-in intelligence for in-situ vibration suppression. Figure 7 shows the schematic diagram of the vibration control circuit with maximum output voltage at ±9V. The piezoelectric sensor signal is amplified and phase-shifted 180° to drive the piezoelectric actuator for active damping control. It is shown in Figure 8 that the bending vibration of the aluminum beam is effectively minimized from 9.5 to 4 seconds. And that of the composite laminated structure is minimized from 10 to 4.2 seconds as also shown in Figure 9. These experimental results indicate that the structural damping is increased by active control from the piezoelectric sensor/actuator. The control induced structural damping can be furthered increased by the increase of feedback gain (control voltage) and/or by the increase of number of piezoelectric actuator.

3. Shape control

Another important application of smart structure is shape control. The linear relation between the mechanical strain of the smart structures and the applied DC voltage in Figure 3 indicates that the piezoelectric effectiveness can be applied to improve shape control accuracy. Figure 10 shows the shape control circuit of the smart structure driven by one 9VDC battery. The objective is to amplify the 9VDC to about 200VDC such that the smart structure mechanical strain can be fine tunedlinearly by the control input. This control circuit also use IC555 to provide the oscillating current, which is then amplified and transformed to direct current voltage to drive the piezoelectric actuator. Experimental result

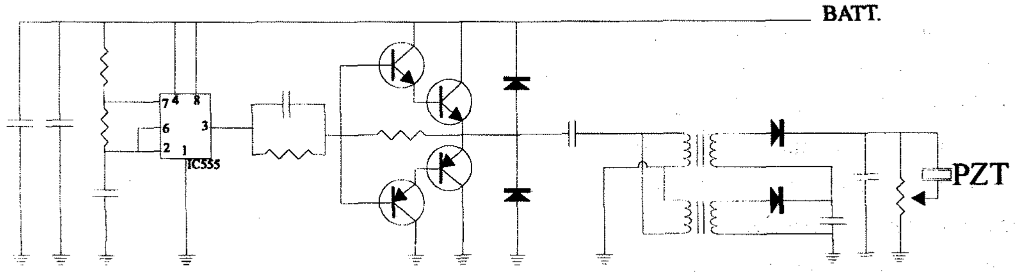

Figure 10. Shape control circuit.

shows that the maximum displacement of the tip of the aluminum beam can deflect 5 mm in a resolution of 20 μ m/volt. This result illustrates that the application of smart structure design in shape control is very effective.

The above results show that the smart structure concept is applicable to advanced aircraft systems with active wing design, aeroservoelastic system, and accurate shape control systems. The ability to use relatively simple drive electronics combined with piezoelectric sensor/actuator of low thermal, and radiation sensitivities and large dynamic range has demonstrated the effectiveness in dither excitation, vibration suppression and shape control.

Conclusions

(1) Two smart structure specimens--an aluminum beam with surface bonded piezoelectric materials and a glass fiber composite laminates with embedded piezoelectric sensor and actuator--are designed, fabricated, and tested for their effectiveness both in vibration control. In addition to modal testing, the smart specimens are also tested for their piezo-effectiveness. Static test results show that the mechanical strain increases in a rather linear relation when the voltage is increased.

(2) In dither excitation, the tip displacement of an aluminum cantilever beam of 400 mm × 30 mm × 1.2 mm can be as high as 35 mm, and that of the composite laminated structure of 270 mm × 40 mm × 1.3 mm is about 15 mm. Any desired dither frequency within the control bandwidth is possible because of the wide dynamic range of the piezoelectric actuator.

(3) In vibration suppression, the bending vibration of the smart structure specimen is suppressed by using a velocity feedback control circuit. The settling time of the cantilever aluminum beam is shown to be minimized from 9.5 to 4 seconds and that of the composite laminated structure is from 10 to 4.2 seconds. Experimental results validate that the smart structure concept can be implemented on-board for effective vibration suppression in aeroservoelastic systems.

(4) In shape control, experimental result shows that the maximum displacement of the tip of the aluminum beam can be fine tuned in the range of 5 mm in a resolution of 20 μ m/volt.

References

1. E. F. Crawley and J. deLuis, "Use of Piezoelectric Actuators as Elements of Intelligent Structures," *AIAA Journal*, vol. 25, no 10, pp. 1373-1385, 1987.
2. S. M. Yang and J. W. Chiu, "Smart Structures--Vibration of Composites with Piezoelectric Materials," *Composite Structures*, vol. 25, pp. 381-386, 1993.
3. A. J. Bronowicki, T. L. Mendenhall, R. S. Betros, R. E. Wyse, and J. W. Innis, "ACESA Structural Control System Design," *Proceedings of the First Joint Japan/US Conf. on Adaptive Structures*, Technomic Publishing, pp. 373-401, 1992.
4. S. M. Yang and J. J. Bian, "Vibration Control of Composites Structures with Embedded Piezoelectric Element," accepted for application in *Smart Materials and Structures*.
5. S. M. Yang, "Stability Criteria of Structural Control with Noncolocated Velocity Feedback," *AIAA Journal*, vol. 31, n. 7, pp. 1351-1353, 1993.
6. S. M. Yang and J. S. Chiu, "Dither Motion Design with Concurrent Sensing and Actuator Piezoelectric Materials," *J. of Smart Materials and Structures*, vol. 3, pp. 248-253, 1994.
7. S. M. Yang and Y. J. Lee, "Modal Analysis of Beam Structures with Piezoelectric Materials," *J. of Sound and Vibration*, vol. 176, n. 3, pp. 289-300, 1994.