AC 2008-2632: SMART MATERIALS AND STRUCTURES EXPERIMENTS FOR UNDERGRADUATE STUDENTS

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Smart Materials and Structures Experiments for Undergraduate Students

Abstract

Smart materials and structures are a new rapidly growing interdisciplinary technology which embraces the fields of materials and structures, sensors and actuators, information processing, and control. To ensure the progress and success of smart materials and structures technology, engineering and technology educators need to make strong efforts to educate the students. At Jackson State University (JSU), two lab modules (Piezoelectric Sensors and Actuators, and Photostrictive Actuators) have been added to several existing courses that have helped undergraduate students develop hands-on experience as well as strengthen students' foundation in smart materials and structures technology. In performing the laboratory assignments, students use the instruments and follow the procedures outlined by the instructors. These two lab modules allow students to gain insight into the smart structures as well as to become knowledgeable users of the equipment. Responses and feedback from students have been very positive.

1. Introduction

A smart structure is a system containing multifunctional parts that can perform sensing, control, and actuation[1,2]. The entire system is integrated to perform a self-controlled smart action, similar to a living creature that can think, make judgment and take action. Smart materials (such as piezoelectric materials) are used to construct these smart structures, which can perform both sensing and actuation functions. Recently, an increasing interest in the development of miniaturized smart structures and systems, particularly on micro and nano electromechanical systems, has evolved into a new page in the science and engineering field. This evolvement establishes a need of integrating technologies from different disciplines. However, most of today's engineering and technology students are unaware of the remarkable properties of smart materials as well as the applications of smart structures technology. Therefore, courses on their behavior and analysis have become necessary for modern engineering and technology students.

This paper describes our attempt at Jackson State University to make smart materials and structures education available to undergraduate students. Two lab modules (Piezoelectric Sensors and Actuators, and Photostrictive Actuators) have been developed to stimulate students' interests as well as strengthen their foundation in smart materials and structures technology. The lab modules, which have been used to incorporate active learning into engineering and technology programs, have given students a deeper, more focused experience with smart materials and structures. Being able to see, touch and interact with entities that demonstrate complex behavior is exciting and appealing for students. A total of 20 students enrolled in the lab modules, which were offered for the first time in Fall 2007. Responses and feedback from students who have taken these two modules have been very positive.

2. Piezoelectric Sensors and Actuators

Piezoelectricity is the ability of a material to develop an electrical charge when subjected to a mechanical strain (direct effect) and conversely, develop mechanical strain in response to an applied electric field (converse effect). Piezoelectrics are available in polymer (polyvinylidene fluoride or PVDF) or ceramic (lead zirconate titanate or PZT) form. Piezoceramics are stiff and brittle, while piezopolymers are compliant and soft. Due to the coupled mechanical and electrical properties, there are two possible ways to utilize piezoelectric materials. First, piezoelectric material can be used as a sensor (direct effect). Second, the piezoelectric material can be used as an actuator (converse effect).

2.1 Experimental Setup

This lab module is to demonstrate the electromechanical properties of piezoelectric materials, as well as to reveal the basic principles of intelligent structure and structural control. The experimental setup is depicted in Figure 1. The setup composes of a cantilever beam, and the piezoelectric patches that are attached to the cantilever and act as sensor and actuator. The controller is implemented on a dSPACE 1104 controller board using MatLab and Simulink software. The controller accepts the input sensor signal and computes the feedback signal. The Model 7500 power amplifier from Krohn-Hite Instruments is used in this experiment to drive the piezoactuator. Besides dSPACE, LabVIEW is also a good choice for this type of experiment.

When a deflection is given to the cantilever beam, the piezoelectric sensor will generate a signal. Once the cantilever beam is forced to vibrate, the piezoelectric sensor will continue to generate the signal. When the controller to the actuator patch is on, the sensor signal will be proceeded by a control algorithm, then the control signal will be amplified and fed back to the actuator to suppress the vibration. This cantilevered beam system is a simple form of smart structures since both the sensor and actuator are integrated parts of the structure. This smart beam has the ability to sense and to react to vibrations.

The test apparatus consists of an aluminum cantilever beam 24.75-inch long, 1.5-inch wide and 0.075-inch thick. The clamped beam boundary conditions are materialized by means of a rigid support that inhibits the translation and rotation of the clamped extremity of the beam. The commercially available PZT patches (QP15W and QP20W from Midé Technology) are used. QP15W works as a sensor and QP20W as an actuator. A PZT patch is bonded near the clamped end on each side of the beam. This position is chosen because the greatest strains occur at fixed end of the beam.

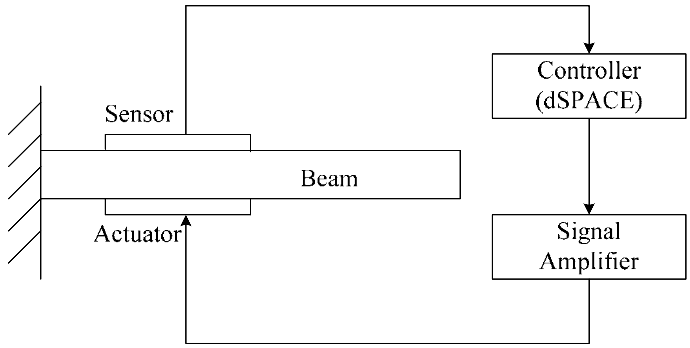

Figure 1. Schematic diagram of experimental setup for vibration control

A laser vibrometer (VibroMet 500) is also used in this experiment to measure the tip displacement and obtain the frequency response of the beam's vibration. Important parameters of the beam (such as natural frequencies and damping ratios) can then be obtained and used to establish the transfer function. Figure 2 shows the free vibration of the beam in open loop after an initial disturbance to its tip. The damping ratio ζ can be determined by measuring two displacements separated by any number of complete cycles. Let x_o and x_n be the vibration amplitudes at initial point and then n cycles later. It is customary to introduce the notation

$$\delta = \frac{1}{n}\ln\left(\frac{x_o}{x_n}\right) \tag{1}$$

where δ is known as the logarithmic decrement. The damping ratio can be obtained by using the following equation[3]:

$$\zeta = \frac{\delta / 2\pi}{\sqrt{1 + (\delta / 2\pi)^2}} \tag{2}$$

The equation of motion of a structural system in modal coordinates can be written as follows:

$$\ddot{q}_n + 2\zeta_n\omega_n\dot{q}_n + \omega_n^2 q_n = 0 \tag{3}$$

where ω_n and ζ_n are natural frequency and damping ratio of the n^{th} mode, respectively; q_n, $\dot{q}_n$ and $\ddot{q}_n$ represent modal displacement, velocity and acceleration, respectively.

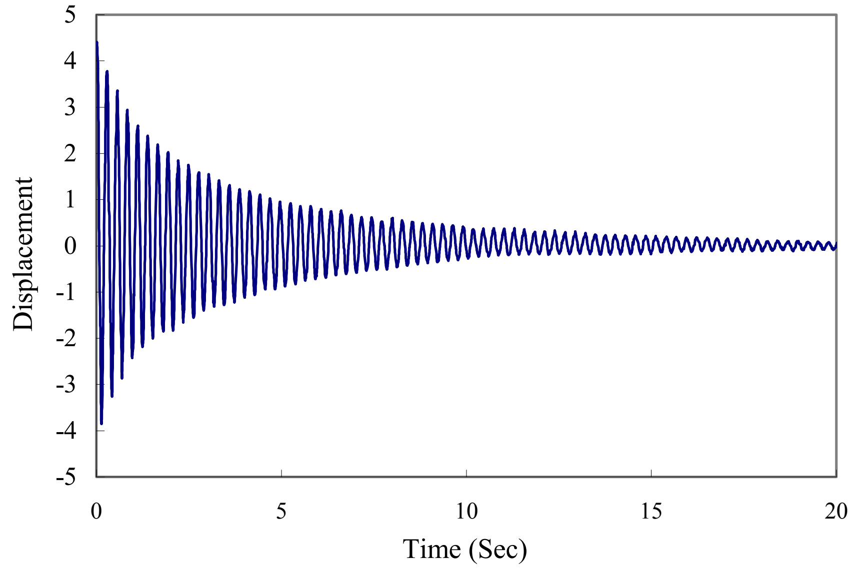

Figure 2. Free vibration of the beam after an initial disturbance at the tip

2.2 Controller Design

An important issue in designing a controller for a flexible structure is whether the developed closed-loop system will have sufficient robustness to deal with uncertainties in the system model. The flexible structures consist of a large number of highly resonant modes and thus the controller has to guarantee stability in the presence of uncontrolled modes. The proper control law can be chosen with help of computer simulations.

Majority of students choose the positive position feedback (PPF) algorithm. PPF control is applied by sending the structural position coordinate directly to the controller. Then the product of the controller output and a scalar gain are fed back to the actuator. Students can adjust the gain to optimize the control performance. The PPF control scheme is shown in Figure 3.

The PPF is developed based on two second-order systems and has the following forms:

$$\ddot{q}_n + 2\zeta_n\omega_n\dot{q}_n + \omega_n^2 q_n = G\lambda \tag{4}$$

$$\ddot{\lambda} + 2\zeta_c\omega_c\dot{\lambda} + \omega_c^2\lambda = q_n \tag{5}$$

where G is the feedback gain, λ, ζ_c, and ω_c represent coordinate, damping ratio, and resonant frequency of the controller, respectively. When the PPF control scheme is implemented on the smart beam, the input of the controller is the displacement output of the structure.

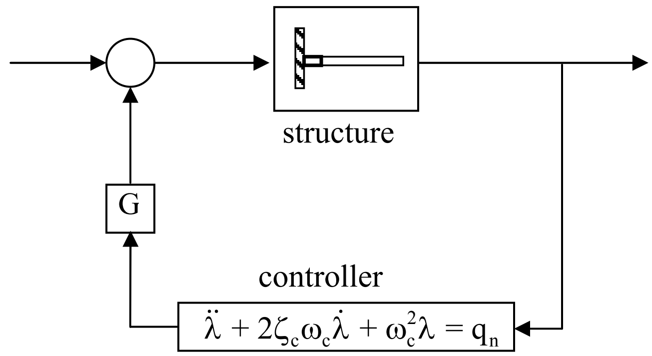

Figure 3. Positive position feedback (PPF) Control Scheme

Here, assume that the response of the beam has the form

$$q_n(t) = A \cos \omega_n t \qquad (6)$$

The output of the controller can be written in the form

$$\lambda(t) = \chi \cos(\omega_n t - \phi) \qquad (7)$$

where χ and ϕ are the amplitude and phase angle of the response, respectively, quantities that are given by

$$\chi = \frac{A}{\sqrt{(1-\frac{\omega_n^2}{\omega_c^2})^2 + (2\zeta_c \frac{\omega_n}{\omega_c})^2}} \qquad (8)$$

and

$$\phi = \tan^{-1}\left({2\zeta_f \frac{\omega_n}{\omega_c}} \Big/ {\left(1-\frac{\omega_n^2}{\omega_c^2}\right)} \right) \qquad (9)$$

The complex frequency response function of Equation (5) is

$$H(\omega_n) = \frac{1}{1-\frac{\omega_n^2}{\omega_c^2} + 2j\zeta\frac{\omega_n}{\omega_c}} \qquad (10)$$

The amplitude-frequency curves are depicted in Figure 4. As shown in Figure 4, the component in the input $q_n(t)$ whose frequency is very close to that of the controller is amplified, whereas those whose frequencies are much lower or higher than the frequency of the controller are depressed. Therefore, PPF controller functions as a special bandpass filter. Equation (9) shows that the phase difference between the output of filter and the input at $\omega_n/\omega_c = 1$ is $\pi/2$.

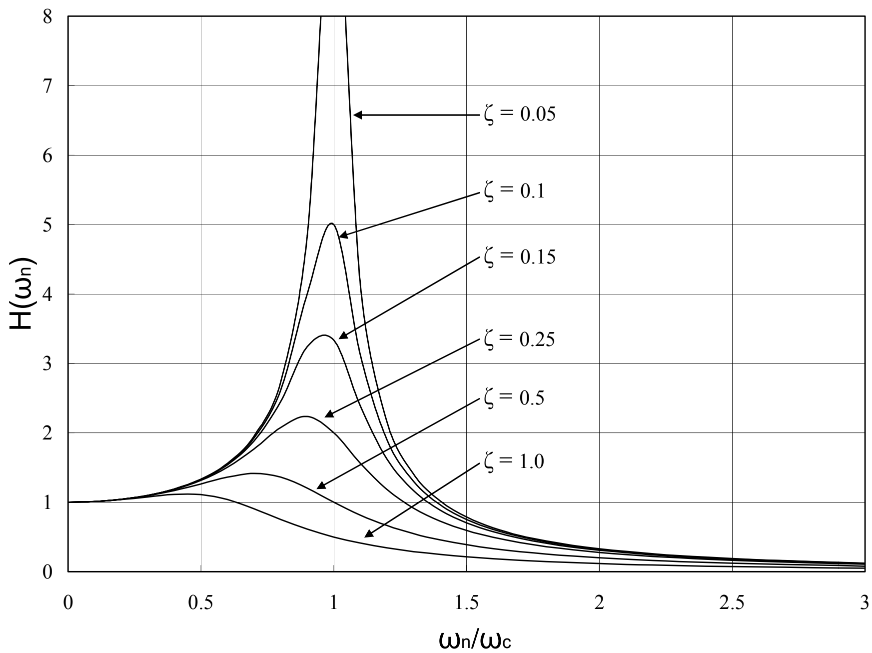

Figure 4. Amplitude-frequency curve

Letting $\phi = \pi/2$, Equation (7) leads to

$$\lambda(t) = \chi \cos(\omega_n t - \frac{\pi}{2}) = \chi \sin \omega_n t = -\chi \dot{q}_n(t) \tag{11}$$

In view of this, Equation (4) can be rewritten as

$$\ddot{q}_n + (2\zeta\omega_n + G\chi)\dot{q}_n + \omega_n^2 q_n = 0 \tag{12}$$

It is shown that the controller reduces resonant responses of the structure by increasing the system damping at the resonant frequency.

In summary, for the PPF control algorithm, the input value of controller block is the modal displacement. The resonant frequency of the second order PPF controller is set to the corresponding structural natural frequency. The phase lag of the controller around the resonant frequency is about 90 degrees. Therefore, the output of the controller is the modal velocity feedback signal. The advantage of the PPF algorithm is that the control energy can be concentrated around the target frequency. Therefore, the control signals have small high frequency components, so that the control energy spillover into the residual modes can be prevented. Thus, the system guarantees closed-loop stability in presence of uncontrolled high-frequency modes.

The control performance has been observed in the time domain by monitoring the transient behaviors of the specimen. The decaying behaviors are presented in Figure 5. It can be seen that the beam oscillation is damped out very fast. The effectiveness of the vibration control provided by the piezoelectric sensor and actuator can be clearly understood.

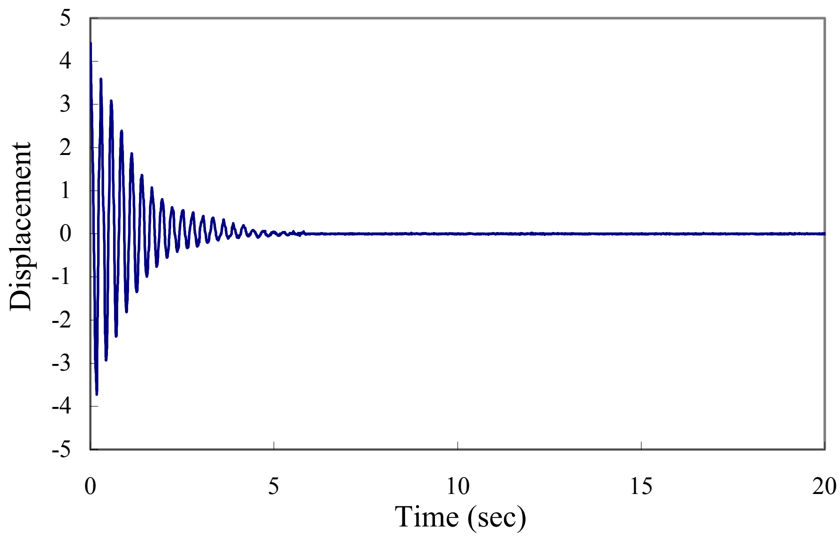

Figure 5. Controlled tip response

3. Photostrictive Actuators

Optical actuator, which can directly convert photonic energy into mechanical motion, is a new promising actuation technique for active control of flexible structures. It offers the advantage of generating distributed actuation strain without connecting any electric lead wires. Photostrictive materials are sensitive to ultraviolet (UV) light. An optical actuator made of photostrictive material is both photovoltaic (producing electricity from light) and piezoelectric (creating motion from electricity)[4-9]. The combination of photovoltaic and piezoelectric effects is also called photostriction. A common material that shows the photostriction is PLZT[5]. PLZT is a special ceramic compound made from lead (Pb), lanthanum (La), zirconium (Zr) and titanium (Ti) with the general formula [(Ph,La)(Zr,Ti)O_3].

A beam structure with a surface-bond photostrictive actuator is shown in Figure 6. The actuator layer is not a simple structural layer. It provides the ability to apply a localized line force and a moment to the structure, as shown in Figure 6. When the high-energy illumination irradiated on the optical actuator, a large voltage is generated between the electrodes through the irradiation of light. This process is known as the *photovoltaic* effect. The induced photovoltaic voltage consequently induces actuation strains as the result of the converse *piezoelectric* effect. The induced strain field can then be used to deform the main body of the host structure.

3.1 Laboratory Exercise

This lab module explores the phenomenon of photoactuation in PLZT and assesses its application potential to precision actuation and control. In the experiment, one photostrictive actuator patch is bonded to one side of a 1.0 mm (0.04 inches) thick plastic beam, which is cantilevered such that its width is vertical, and its thickness is horizontal to allow bending of the beam to take place in the vertical plane. The beam has a length of 15 cm, 3 cm of which is held in the clamp, and a width of 5 mm. The actuator patch is 15 mm long, 5 mm wide and 0.4 mm thick. The 5×0.4 mm^2 surface was electroded with silver paste. The actuator is placed at 2 cm from the root of the cantilever beam. The second actuator, with the same dimensions as the first one, is bonded on another side of the beam. Two PLZT actuators are placed in opposite polarization. A conductive pen is used to draw conductive silver traces between the edges of the actuators. Thus, these two actuators are connected on the edges electrically. In this experiment, the PLZT actuators are provided by the Materials Research Laboratory at Pennsylvania State University.

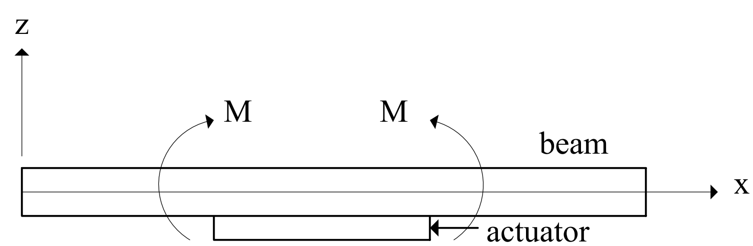

Figure 6. A beam with a surface-bond photostrictive actuator

An UV laser is used as light source. In the experiment, the laser beam is irradiated on the actuator. The laser light power is varied to examine the effect of light intensity. By adjusting the UV wavelength selector, a light beam with a maximum strength around 364-nm wavelength can be obtained. Light with the wavelength peak around 366 nm has been reported to yield the maximum photovoltaic property[5]. The laser beam diameter is around 2 mm. A laser beam expander is used to enlarge and collimate the laser beam. The output (from the expander) beam aperture diameter is 2 cm. Thus, the distribution of UV light over the actuator surface becomes uniform.

The 364-nm light is focused on one actuator. The light irradiating results in a photodeformation process and an expanding of the actuator[4,8]. However, the actuator on the other (unlit) side of the beam contracts due to the piezoelectric effect through the photovoltage. To explain this phenomenon, a diagram is illustrated in Figure 7. Since these two actuators are bonded on the beam, the whole system (beam with two actuators) bends away from the direction of irradiation of the light. A fiber optical sensor (DMS-D63 from Philtec) is used in this experiment to detect this movement. The sensor probe is mounted on a minivise and is aimed at the tip of the beam. A computer interfaced with the sensor is used for data acquisition. The experimental setup is shown in Figure 8.

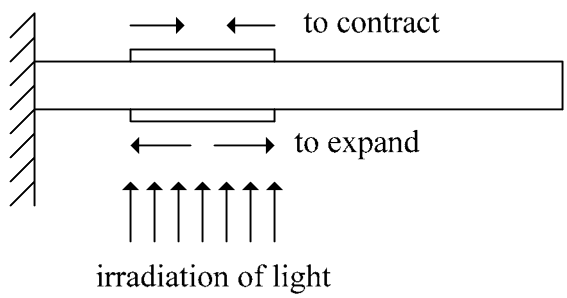

Figure 7. A photo driven beam and its driving principle

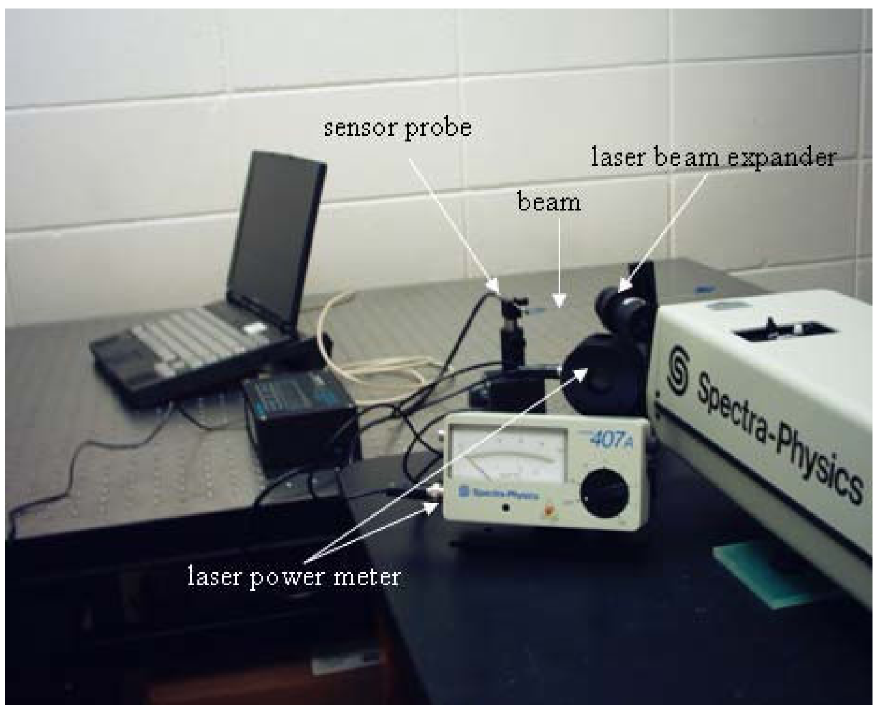

Figure 8. Experimental setup

3.2 Results

Shown in Figure 9 is the experimental measurement of the cantilever's tip displacement after exposure to 364-nm light. Total measurement time is 45 seconds. The UV light is irradiated constantly for the entire time. The experiments are conducted for three cases of light power (20 mW, 30 mW and 40 mW). The illumination intensity can be calculated by dividing the light power by the area of the light beam, which is π cm^2 in this experiment.

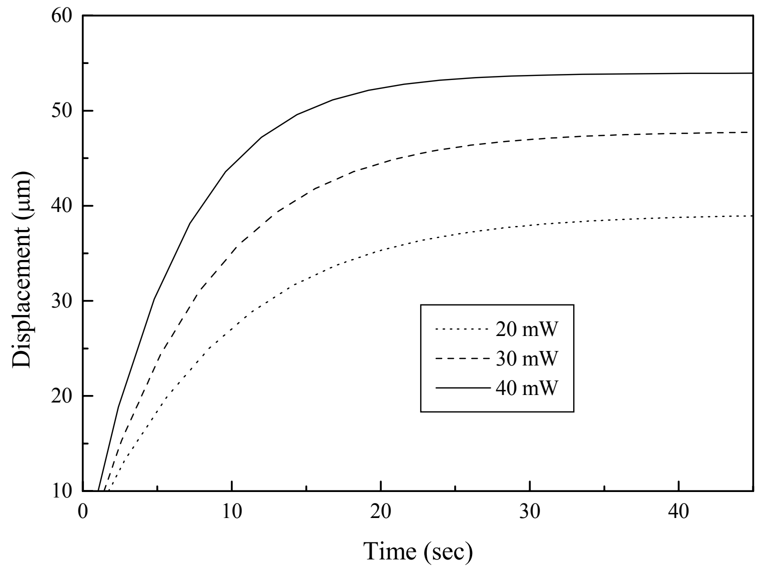

Figure 9. Time history of displacement of a cantilever beam by irradiation at different illumination intensities

From Figure 9, it can be seen that the beam tip displacement reaches 54 μm after 24 seconds irradiation of 40/π mWcm^{-2}, and then the displacement remains constant. In case of 30/π mWcm^{-2} irradiation, it take 26 seconds for the cantilever's free end to get to 46 μm of photodeflection followed by a very slow increase in deflection. For the 20/π mWcm^{-2} irradiation, the result shows a similar trend with that from the 30/π mWcm^{-2} case. It takes 30 seconds for the tip displacement to reach 38 μm, and then the displacement increases very slowly. For each case shown in Figure 9, the displacement first increases rapidly and then saturates to a constant value. It is also observed that the response time and displacement depend on the intensity of UV light irradiation.

This lab module can be carried out with few instruments, but at the same time explains to students the complicated properties (photovoltaic and piezoelectric) of the photostrictive devices.

4. Student Surveys

A total of 20 students enrolled in the lab modules, which were offered for the first time in Fall 2007. At the end of the semester, students were asked to fill out an anonymous survey which included ranking the effectiveness of the smart material experiments. The result is shown in Figure 10. In view of the result, it is clear that most students thought these experiments were effective. The following are some students' comments:

· Being able to measure the beam bending and vibrating really helps to understand the concepts behind it.
· It is good to use equipment and makes the material easy to learn.
· Both theory and practical examples should always be taught at the same time, like this lab did.

These comments clearly show these lab modules are effective. The lab modules not only offer students state-of-the-art learning tools, but also provide students with a firm grasp of the smart materials and structures technology.

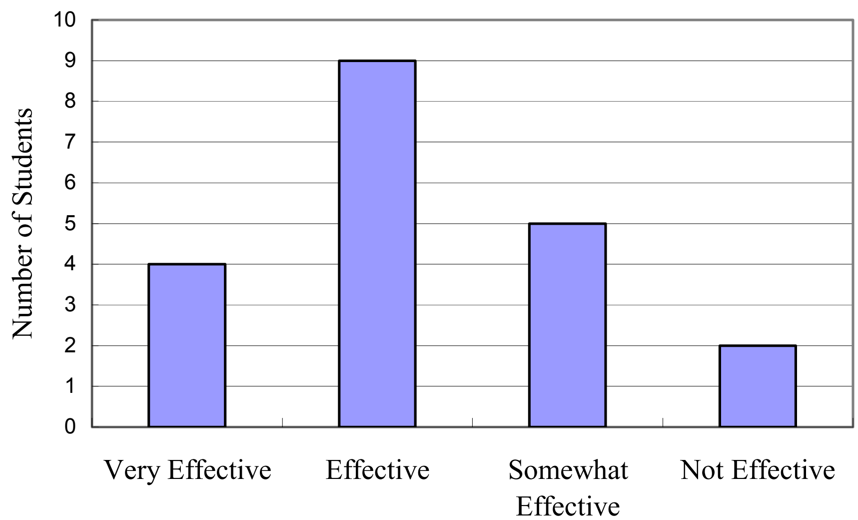

Figure 10. Students' evaluation of the effectiveness of the lab modules

5. Conclusions

Smart materials and structures are a rapidly advancing field. In order to offer students a more tangible understanding of this emerging technology, two lab modules in smart materials and structures have been introduced into undergraduate technology and engineering curriculum. Students have an opportunity to experiment with piezoelectric and photostricitve materials. Students taking this course have gained an appreciation of the state-of-the-art smart structures technologies and learned the main concepts of smart structural systems. Positive feedback from the students' survey shows these modular laboratory exercises are effective in helping to bridge the gap between theory and intuition during the students' learning process.

Acknowledgments

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