# AC 2008-1193: A MULTI-FUNCTIONAL, SMART, FLEXIBLE, VERTICAL, CANTILEVERED BEAM EXPERIMENT TO IMPROVE UNDERGRADUATE EDUCATION

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# A Multifunctional Smart, Flexible, Vertical, Cantilevered Beam Experiment to Improve Undergraduate Education


## Abstract

This paper presents the development and application of a smart, flexible, vertical cantilevered beam system for experimentation and demonstration of vibration system modeling as a reinforcement to undergraduate dynamics education. Focusing on the difficult concepts of transfer functions and frequency domain based analysis, the beam system aids students in grasping basic vibration system concepts by allowing them to analyze and manipulate real system data collected through a simple and inexpensive piezoceramic-based data acquisition and actuation system. Students observed and analyzed the dynamic responses of a flexible aluminum beam subjected to various input signals to draw conclusions and relationships between system input and system response through the use of Bode diagrams, relationships often difficult for students to appreciate without experimental experiences. Results from post-demonstration student surveys indicate that the students found the demonstrations of the flexible beam system to be exceptionally effective in improving and motivating learning in their courses, with 94% of student responses rating the beam system as "effective" or "very effective" in various aspects of the demonstration.


## Introduction

A common limitation of traditional engineering education is the weakness of presenting theories and techniques in a way that students can link to real-world experiences or pre-existing intuition. For many students, the largest obstacle to full comprehension of course material is a disconnect between the lecture-based teaching style traditional in engineering and the student's own experience-based learning style [1,2,3]. For those students, course concepts are not completely understood until they are able to see or experience the concept implemented in the real world. One such instance occurs in the teaching of system dynamics, where multiple methods of modeling and interpreting a system's dynamics and responses are taught[2,4]. While Ordinary Differential Equation (ODE) modeling and time-based representation of system responses are approachable by most students due to their familiarity with ODE and the intuitiveness of time-based domain, students have a difficult time understanding the transfer function modeling of a system and frequency domain analysis. Due to little previous exposure to and limited real-world experience with these two subjects, students struggle to conceptualize the subjects and their advantages in data and systems analysis. However, education research in engineering has shown that experience-oriented labs and demonstrations are effective at bridging the gap between abstract concepts and true knowledge in students with experience-based learning styles[5,6]. Development of demonstrations to target these subjects would dramatically help students in their understanding of transfer function modeling and frequency domain analysis, giving them a real-world experience to reference.

This paper describes a flexible beam demonstration/experiment, using a smart material to both activate and sense its response. Though universities have used flexible, cantilevered beam experiments previously to re-enforce vibrations and system dynamics courses, the novel integration of the innovative piezoceramic technology allows a clearer, more accurate representation of the system dynamics[1,4,7, 8] with a lower cost to the university than traditional set-ups. Thus, the demonstration/experiment seeks to improve the quality of education with a minimal increase in cost.

## Educational Goals

The main objective of the smart flexible beam demonstration/experiment is to use state-of-art smart materials (materials capable of transforming one form of energy (mechanical, electrical, or thermal, etc.) into other forms of energy in useful quantities) technology to develop both in-classroom demonstrations and hands-on experiences to improve student's learning in system dynamics, controls, mechatronics, and smart structures (structures with smart materials integrated into their construction) related courses. The foremost goal is to improve student comprehension of basic course concepts, most notably the concepts of vibration, resonance, and frequency domain based analysis. Though the designed smart flexible beam is not a detailed recreation of an actual mechtronics or smart-structural system, the intent of the beam experiment is to provide a basic platform through which students can observe and implement course concepts of system dynamics and system control. Furthermore, this experiment will increase student exposure to smart materials. Smart materials are becoming more common in engineering actuation and sensing applications, students receive limited exposure to them in their formal education. By incorporating the use of smart materials into in-classroom demonstrations of common system dynamic concepts, students are better prepared to use and manipulate these materials in their future careers.

## Piezoceramics

Piezoelectric (or simply "piezo") materials exhibit the piezoelectric effect, that is, creating an electrical field when a mechanical stress is applied and, conversely, mechanically deforming when an external electrical field is present. The piezoelectric effect occurs in materials whose crystalline structure has no center of symmetry. Important examples of these materials are the ferroelectrics, such as barium titanate and lead zirconate titanate (PZT). The unique ability of piezo materials to both deform under an electrical stimulus and to generate a voltage under a mechanical stimulus allows them to act as both a solid state actuator and sensor. Further, thin sheets of PZT can be surface bonded or otherwise structurally integrated into a system, allowing for easy implementation in a dynamic system, and the nearly linear proportionality between the mechanical strain and the applied/sensed voltage allows for easy control of PZT behavior.

## The Flexible Beam System

A horizontal and a vertical flexible beam have been developed as educational tools. The vertical beam presented here is based on the horizontal beam system developed in previous work [9, 10] and was developed as a senior capstone design project. The vertical beam system is composed of a simple, vertically-cantilevered, flexible aluminum beam outfitted with both a PZT actuator and a

PZT sensor at the cantilevered base to maximize the PZT strain effect. It is self-contained within a clear acrylic case as seen in Figure 1. Detailed physical parameters of the beam are given in Table I. The first four harmonic frequencies of the beam were determined experimentally and programmed into the control module.

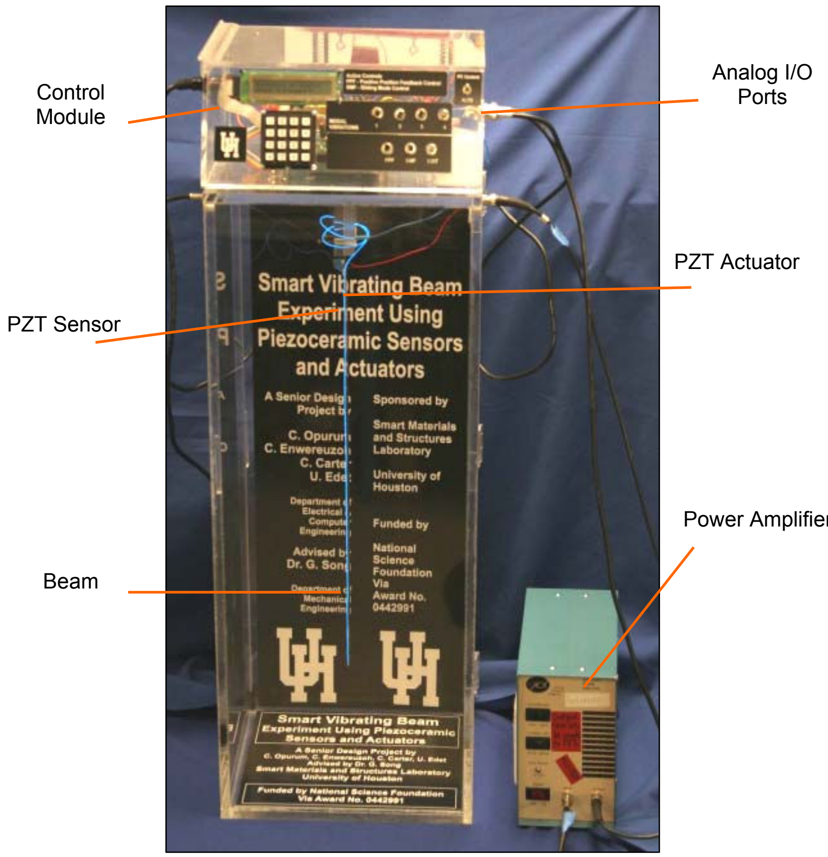



Figure 1: Smart Flexible Beam Experiment

An Active Control Quickpack™ PZT amplifier was used to amplify the actuation signal to the PZT actuator. Real-time control was implemented with a dSpace ™ CLP1104 data acquisition board with integrated ADC/DAC capability. Simple excitation signals used in the demonstrations were generated on portable signal generators. Data were collected and sent to a dSpace™ enabled PC and viewed in real-time on a locally connected oscilloscope. Built in functionalities, described later in this paper, were programmed and controlled on a MC9S12C32 Freescale™ microcontroller housed in a separate control module with push-buttons and switches for user input, and an LCD display screen for user interaction. A fiber-optic cable was attached to the edge of the beam to give visual definition to the beam's movement.

A more detailed schematic describing the actuating and sensing component of the flexible beam is presented in Figure 2. The actuator patch is sent an actuation signal from either a function generator or a PC via the DAC channel from the dSpace™ board which is amplified by the PZT

Table I: Flexible Beam Physical Parameters

| ***Symbol*** | ***Quantity*** | ***Units*** | ***Value*** |
|---|---|---|---|
| L | Length | (mm) | 529.9 |
| W | Width | (mm) | 48.7 |
| T | Thickness | (mm) | 0.68 |
| ρ | Beam density | $kg/m^3$ | 2690 |
| **E** | Young's Modulus | $N/m^2$ | $7.03 \times 10^{10}$ |

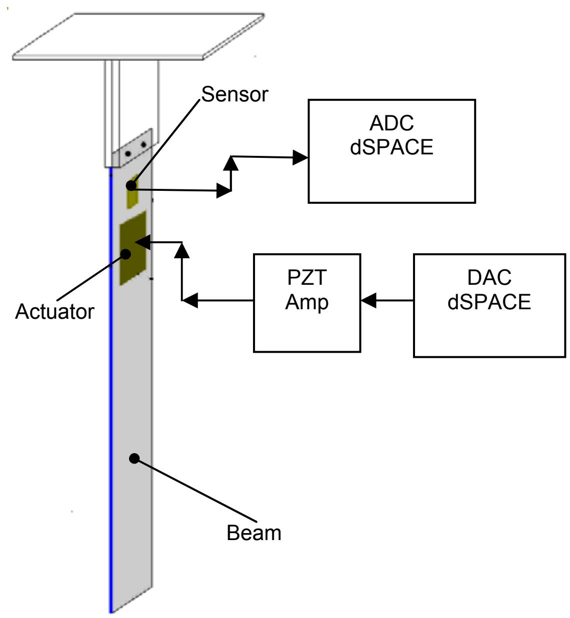



Figure 2: Schematic Operation of Flexible Beam

amplifier. Simultaneously, as the beam moves, the sensor patch is strained and the voltage generated in the sensor patch is recorded through the ADC channel of dSpace™ board. The proportionality of strain to the sensed voltage allows for a direct correlation between the sensed voltage and the vibration amplitude of the beam. Virtual Instruments can be programmed to analyze the excitation and response signals in graphical form, providing either time-histories of the signals or generating real-time Bode plots.

Furthermore, advanced programming of the microcontroller allows preset operation procedures of the beam for simple demonstration purposes. A photograph of the command module for these functions is shown in Figure 3. Custom excitation frequencies can be activated through the key pad and LCD display. In “Auto” mode, actuation of the beam at the first four modal frequencies was programmed to mutually exclusive push-buttons on the control module. Positive Position Feedback (PPF) and Sliding Mode (SMF) controllers were also pre-programmed to the microcontroller and are operated through push-buttons. The microcontroller also has the capability for more advanced control of the beam for experimentation in “PC Control” mode, allowing for custom control schemes to be uploaded and implemented onto the controller. Thus, the microcontroller allows the smart flexible beam system to act as both a demonstration and an experiment.

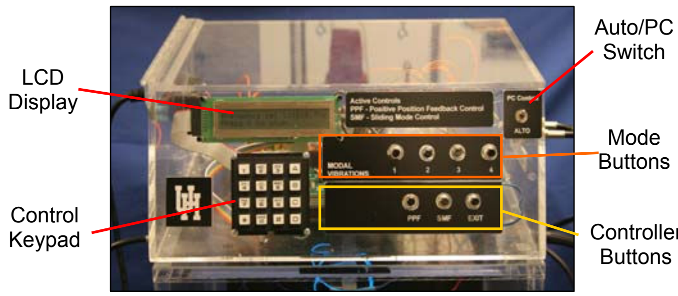
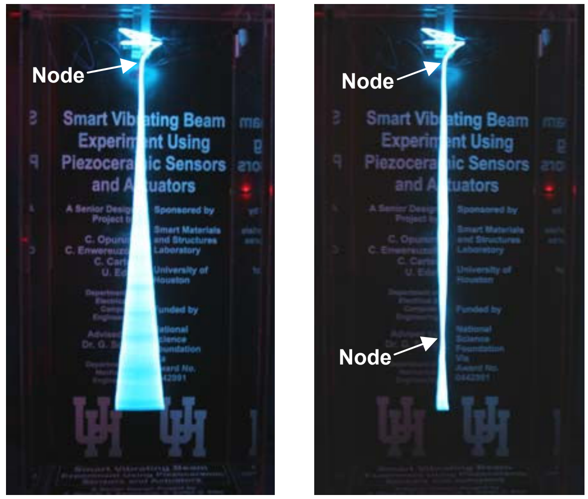



Figure 3: Smart Beam Control Module

**Smart Beam Demonstrations**

A set of demonstrations were developed using the smart, flexible beam to illustrate topics in dynamics, frequency response, and vibration control to students. For these demonstrations, the control module was set to “Auto” and the push-button controls were used to activate the preset control actions. Resonance and modal shapes were demonstrated by actuating the beam at its modal frequencies. The modal shapes for the first two modal frequencies are presented in Figure 4. Students were also presented with the Bode plots, seen in Figure 5, of the smart flexible beam system, in which the modal frequencies were indicated as peaks in the magnitude plot. Students were then able to draw connections between graphical representations of frequency based response and real, physical responses in a dynamic system. By presenting both the frequency response in the Bode diagram with the physical response seen in the beam, students are able to correlate the increases in gain represented in the Bode plot as rises and peaks with the physical phenomenon observed as vibration magnitude and modal shapes in the beam.

Both PPF and SMF controllers were also demonstrated to illustrate the capabilities of PZT in vibration control. First, the beam was actuated by a simple step input and allowed to vibrate freely without control. Next, the beam was actuated by the step input and one of the controllers was implemented to assist in the control of the beam’s vibration. In both the free and controlled demonstrations, the sensor data was displayed in real-time on an oscilloscope and captured by a PC. In addition to the qualitative comparison made by the students of the time in which the beam ceased vibrating, a graphical comparison of the vibration time histories was constructed from the collected data and presented to the students, as in Figure 6. From the comparison, students could make concrete connections between PZT and the efficacy of vibration control.




(a) (b)

Figure 4: (a) First and (b) Second Mode Operation of Smart Flexible Beam

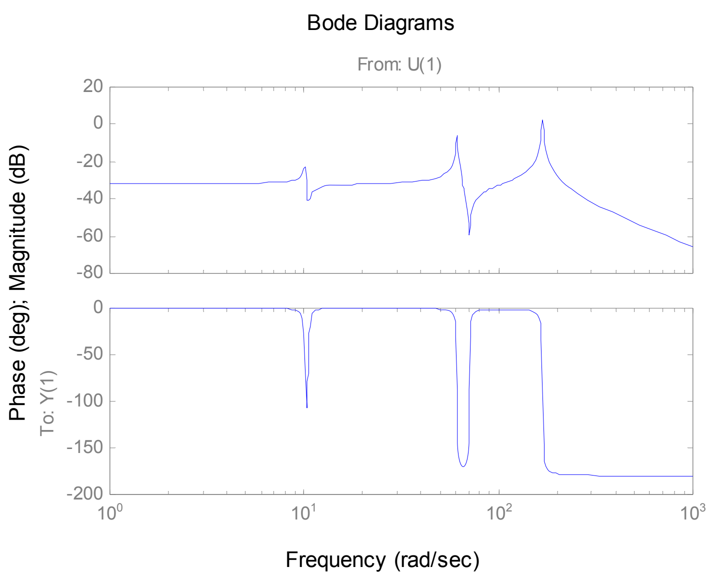



Figure 5: Bode Plot of Smart Flexible Beam System

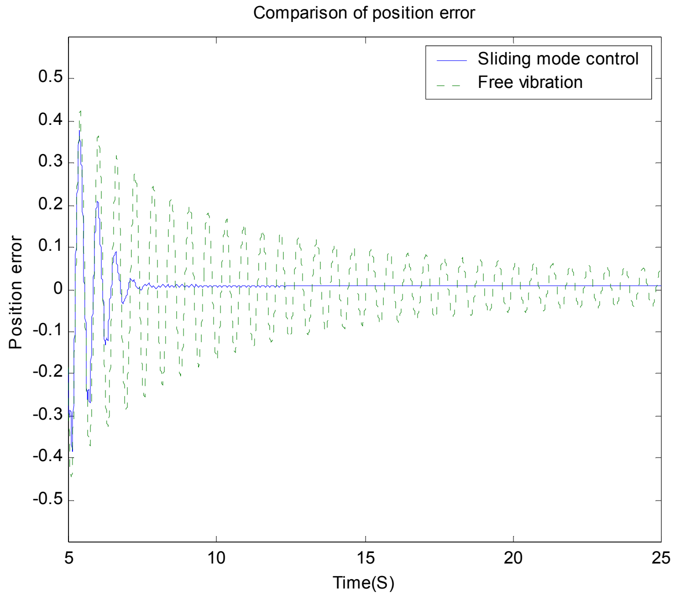



Figure 6: Comparison of Beam in Free Vibration and Beam with Sliding Mode Control

## Proposed Student Lab Experiments

The smart flexible beam was designed to also allow students to use the beam as a test platform for dynamics and controls related experiments. Due to the simplicity of the beam's design, the flexible beam system is able to accommodate a number of labs to address dynamics and controls course concepts. Proposed lab experiments include:

- System Characterization – Students can apply system characterization techniques learned in class to determine system parameters, such as damping ratio and natural frequency. Students can then observe the physical effects of these parameters on the system.
- System Response Identification – Using the actuating and sensing abilities of the smart flexible beam, students could simply actuate the beams vibration and use the sensing element to observe and record the response of a second order system to a variety of inputs. Comparisons of ideal model responses with the experimental responses could be compared to improve student understanding of noise, disturbances, and experimental limitations. Furthermore, comparisons with ideal models can illustrate to the student clearly what their mathematical calculations manifest as in a physical system. An understanding of error and discrepancies would be developed to build the student's understanding and interpretation of experimental research.
- Vibration Control Implementation – Students could implement their designed controllers on a physical system and test the efficacy of their controller. Since the smart flexible also allows manual or PC control of the system, a wide range of controllers can be implemented, such as simple RC based controllers built on

breadboards or programmed controllers built in Simulink. For more advanced courses, the micro-controller allows for the remote upload of controllers to the smart beam, allowing for complex controllers to be implemented and tested with a wide range of inputs that can be changed without altering the Simulink file.

- Remote Controller Testing – Again, the micro-controller's ability to allow programmed controllers to be downloaded to the smart beam's hardware allows the remote implementation of control schemes. However, it should be noted that this ability extends to remote implementation of controllers. The implementation of remote controlled laboratories with student access over the internet using the smart flexible beam with a similar electronic architecture has previously been reported [8]. Through the use of web-based virtual instruments (VI), students could access the smart beam hardware remotely. The VI allows students to upload their controller, initiate testing, and to collect experimental data. The data can then be accessed and downloaded from a remote web server for further analysis.

These proposed laboratory experiments are examples of possible educational laboratory uses of the smart flexible beam. More detailed descriptions of such laboratory and experiment implementations of the smart flexible beam in engineering education are planned.

**Student Survey Results**

Both the vertical and horizontal smart flexible beams have been demonstrated in several engineering courses in different, but related, disciplines. Students completed anonymous surveys following the demonstration of the smart flexible beam to evaluate the ability of the beam to achieve its teaching goals. Students were asked to rate the smart flexible beam as either "Very Effective," "Effective," "Somewhat Effective," or "Not Effective" in demonstrating various concepts related to the course in which the beam was demonstrated. Respondents were asked to evaluate the smart flexible beam's effectiveness in improving student learning simple concepts such as vibration, resonance, vibration control, and feedback control. Additionally, respondents evaluated the smart beam's ability to introduce the concept of smart materials, to introduce the usage of the PZT material as an actuator/sensor, and the ability of the smart beam to motivate continued learning in the area of smart materials. A summary of the survey results is presented in Table II. From the table, it can be seen that the smart flexible beam was well received by the students at all demonstrations, regardless of discipline. The overall effectiveness as perceived by the students of the smart flexible beam to assist student understanding of course concepts is overwhelmingly positive, with over 94% of all responses rating the smart flexible beam as either "Very Effective" or "Effective" in accomplishing its teaching goals. Furthermore, analysis of responses to individual questions indicates that the smart flexible beam was exceptionally effective in accomplishing specific teaching goals. Figures 7 and 8 give the students response distributions for two specific questions asked on the survey administered to the Monterrey Technical Institute group.

From these two responses, it can be seen that the smart flexible beam was successful in fulfilling the two major teaching goals: (1) to assist in the understanding of vibration and resonance and (2) to motivate students to learn more about smart materials, such as PZT. Responses to other questions also indicated that students found the smart flexible beam to be effective in demonstrating PZT as an actuator and sensor, the PZT material in general, and the concept of resonance.

Table II: Survey Results for Smart Flexible Beam Demonstrations

| Course Information [Horizontal (H) or Vertical (V)] | No. of Students | No. of Quest. | Very Effective | Effective | Somewhat Effective | Not Effective |
|---|---|---|---|---|---|---|
| Monterrey Technical Institute Visitors, University of Houston Campus, Dr. G. Song, Nov. 3, 2007 (V) | 23 | 7 | 63% | 32% | 5% | 0% |
| Alvin Community College, Alvin, TX, April 2006 (H) | 9 | 7 | 57% | 37% | 6% | 0% |
| Materials Science, Mech. Eng. Dept, University of South Alabama, Dr. J. Gou, March 2006 (H) | 13 | 7 | 79% | 19% | 2% | 0% |
| Vibration Analysis and Synthesis, Mech. Eng, University of South Alabama, Dr. Engin, 2006 (H) | 14 | 6 | 86% | 11% | 4% | 0% |
| Introduction to Mech. Eng, University of Houston, TX, Dr. G. Song, Oct. 31, 2006 (H) | 12 | 6 | 56% | 38% | 6% | 1% |
| Introduction to Mech. Eng, University of Houston, TX, Dr. G. Song, Oct. 31, 2006 (H) | 18 | 6 | 76% | 19% | 5% | 1% |
| Introduction to Mech. Eng, University of Houston, TX, Dr. G. Song, Oct. 24, 2006 (H) | 19 | 6 | 77% | 17% | 5% | 1% |
| Introduction to Mech. Eng, University of Houston, TX, Dr. G. Song, Oct. 24, 2006 (H) | 18 | 6 | 65% | 27% | 8% | 0% |
| Mech. Tech, University of Houston, TX, Mr. V. Parthi (H) | 24 | 8 | 58% | 38% | 5% | 0% |
| **Total** | **150** | **993** | **68%** | **27%** | **5%** | **< 1%** |

(v) vertical beam
(h) horizontal beam

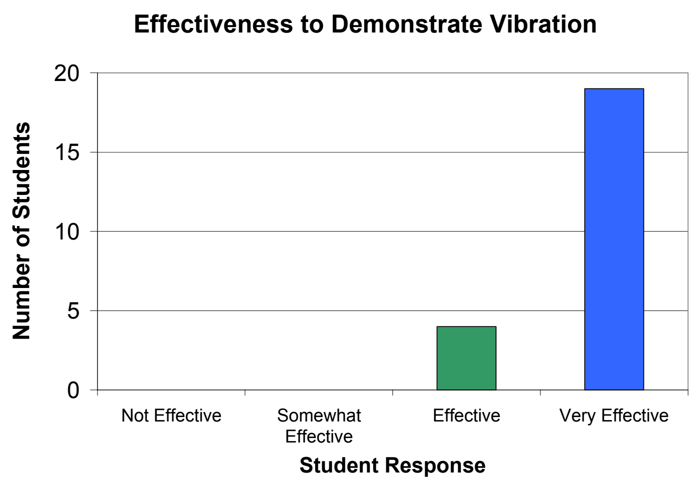



Figure 7: Student Responses Indicating the Smart Flexible Beam's Effectiveness in Demonstrating Vibrations –Monterrey Tech

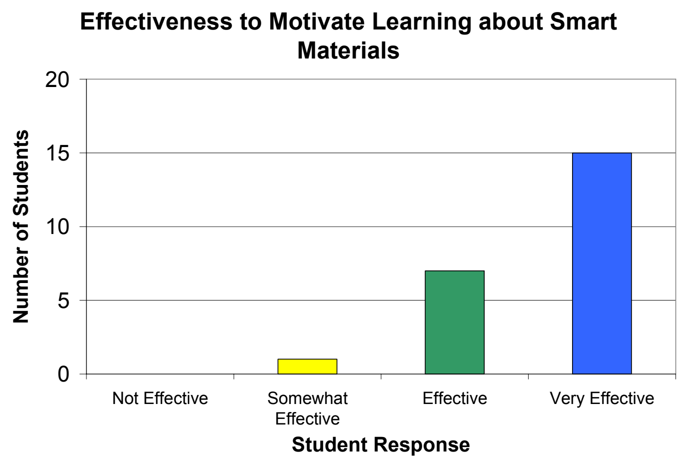



Figure 8: Student Responses Indicating the Smart Flexible Beam's Effectiveness in Motivating Learning about Smart Materials – Monterrey Tech

Additionally, the smart flexible beam has shown itself to be effective at introducing course concepts in system dynamics courses. Figures 9 and 10 present selected student response histograms for the Spring 2008 Dynamics and Controls of Mechanical Systems at the University of Houston. The smart flexible beam was presented to the students on the first day of class as a course introduction.

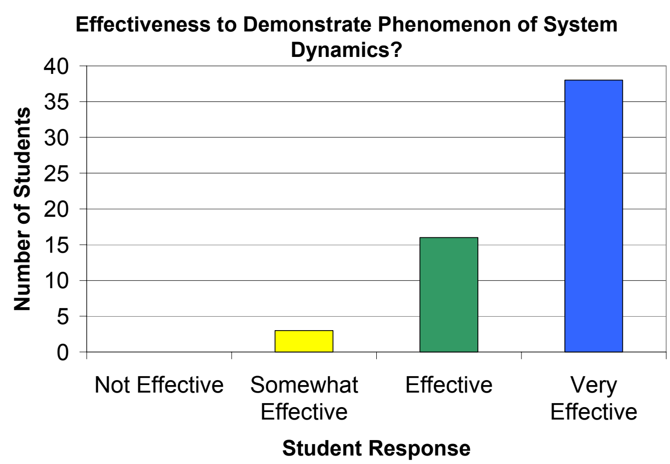



Figure 9: Effectiveness to Demonstrate of System Dynamics - Dynamics and Controls of Mechanical Systems Course –University of Houston

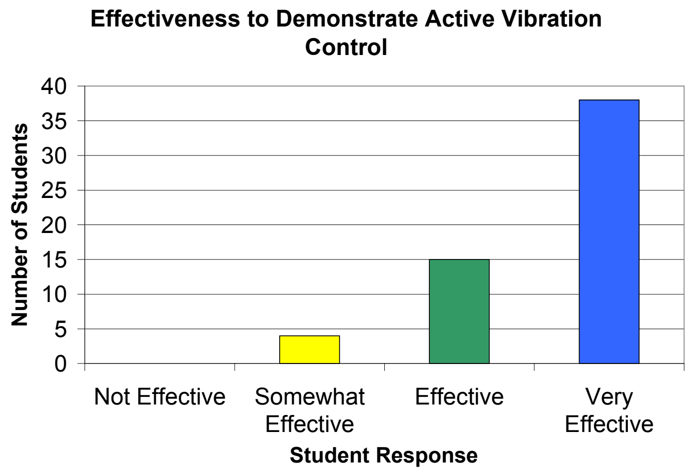



Figure 10: Effectiveness to Demonstrate Active Vibration Control - Dynamics and Controls of Mechanical Systems Course – University of Houston

From both figures, it can be seen that the students found the demonstration to be effective in demonstrating important core concepts and in introducing these concepts in an experiential fashion. Many students commented that they were appreciative of the visual nature of the demonstration, noting that they were visual learners and benefit greatly from seeing course concepts in action. Equally import is that students commented that the demonstration increased their interest in the course and the material. Figure 11 shows the student ratings of the demonstration with regards to effectiveness to motivate learning about dynamics. In the survey, 89% of the students found the demonstration to be effective or very effective at motivating them to learn more about dynamics and vibrations. Of 57 students, only 6 students found the demonstration to be somewhat effective or not effective in motivating them to learn more about dynamics and vibrations. Responses regarding the effectiveness of the demonstration in other respects were also overwhelmingly positive.

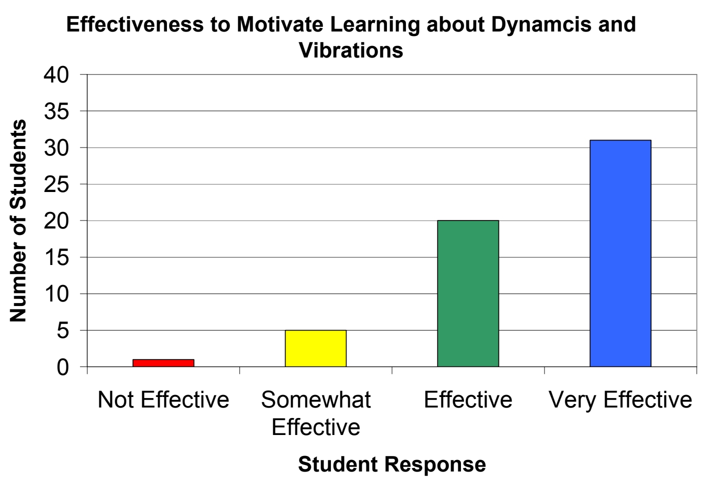



Figure 11: Effectiveness to Motivate Learning about Course Concepts - Dynamics and Controls of Mechanical Systems Course – University of Houston

## Conclusions

A smart, flexible, vertical, cantilevered beam has been designed, developed, and demonstrated as an educational tool to assist in the teaching of dynamics, vibrations, and vibration control. A PZT material was used both as an actuator and a sensor to alert students to the existence of emerging smart materials. In addition to basic vibration concepts, such as resonance and modal shapes, more advanced vibration concepts, such as frequency response and vibration control, were also presented to the students in a single smart, flexible beam demonstration/experiment. Student surveys indicate that the smart flexible beam is effective in fulfilling the teaching goals of reinforcing the concepts of vibration and vibration control. With over 94% of student responses rating the smart flexible beam as at least "Effective" in accomplishing various teaching goals, it is clear that not only is the smart flexible beam an exceptionally effective teaching tool, but also a powerful demonstration for visually presenting basic vibration dynamics principles to a variety of students in various engineering and physical science disciplines.

## Future Work

This paper has shown the smart flexible beam to be an effective demonstration tool. The next stage of this project is to design and develop laboratory modules using the smart flexible beam as the testing platform. Utilizing the dSpace™ data acquisition system implemented and described in this paper, students would be able to use the smart flexible beam as a test bed for simple dynamics and vibrations experiments, collecting and recording data through the PZT sensor and dSpace™ board. Additionally, utilizing the programmable microcontroller in the control module, students will be asked to design vibration control algorithms in SimuLink™ for simple excitations which will be downloaded on to the microcontroller, implemented, and tested for efficacy. There are also plans to develop the smart flexible beam test bed with internet access, allowing remote control and operation of the beam. Students would be able to access the beam from their homes, as well as record data remotely, download recorded data on demand, and test designed controllers remotely.

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## Bibliography

1. Ellis, G.W. and Rudnitsky A.N. and Scordilis, G.E. "Finding Meaning in the Classroom: Learner-Centered Approaches that Engage Students in Engineering," *International Journal of Engineering Education*, 2005, Vol. 21, No. 6, pp. 1148-1158.
2. Felder, R.M. and Brent, R. "Understanding Student Differences," *Journal of Engineering Education*, 2005, Vol. 21, No. 1, pp166-177.

3. Felder, R.M. and L.K. Silverman, "Learning and Teaching Styles in Engineering Education," *Journal of Engineering of Education*, 1988, Vol. 78, pp.674-681, 1988.
4. Dollár, Anna and Steif, Paul. "Learning Modules for Statics." *International Journal of Engineering Education*, 2006, Vol. 22, No. 2, pp. 381-392.
5. Ambrose, S. A. and C. H. Amon. "Systematic Design of a First-year Mechanical Engineering Course at Carnegie Mellon University," *Journal of Engineering Education*, April, 1997, pp. 173-181.
6. Bannerot, R. and G. Song, "Development of an Interactive MR Fluid Experiment for Smart Material Curricula" *International Journal of Modern Physics B*, 19 (7-9): August 10, 2005, 1478-1484 Part 2 Sp. Iss.
7. Felder, Richard M. "Reaching the Second Tier: Learning and Teaching Styles in College Science Education." *Journal of College Science Teaching*, 1993, Vol. 23, Issue 5, pp. 286-290.
8. Olmi, C., G. Song, and Y. L. Mo. "An Innovative and Multi-Functional Smart Vibration Platform," *Smart Materials and Structures,* 2007, Vol. 16, pp. 1302-1309
9. Song, G. and P. Lam, "Improve Teaching of System Dynamics and Response Using Smart Material Experiment," *Journal of Science Mathematic Engineering Technology Education: Innovations and Research*, 2/3&4, September-December, 2001, pp. 11-18.
10. Song, G., M. Zeng, and P. Lam, "A Simple but Effective Experiment to Illustrate Second Order Dynamic Systems," *Proceedings of National Educators' Workshop* (San Jose, CA) (NASA/CP-2003-212403), 2002, pp. 107-115.