# Improve Teaching of System Dynamics and Response Using Smart Material Experiment*

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## Abstract

The goal of this paper is to present simple but effective classroom demonstrations and experiments for mechanical engineering students who are taking System Dynamics and Response (SDR). By taking advantage of the rapid development in the field of smart materials and smart structures, piezoelectric ceramics are used in this project as both smart sensors and smart actuators to help study the dynamics and response of a simple dynamic system – a cantilevered flexible beam. Unlike a traditional experimental setup that is often single purposed, this setup is multi-purposed by utilizing smart sensors and actuators. Many experiments and demonstrations, such as identifying transfer functions, predicting and observing resonance and understanding Bode diagrams, can be derived from this setup. This setup has been built and integrated into SDR as a tool for classroom demonstrations. It is found that these demonstrations help to bridge the gap between theory and intuition during a student's learning process. In addition, these demonstrations have motivates students to further pursue studies in smart structures.

**Keywords: Teaching of System Dynamics and Response, Smart Materials and Structures, Cantilevered Flexible Beam, Vibrations, Linear Systems.**

## Introduction

System Dynamics and Response (SDR) is a core engineering course for undergraduate students majoring in mechanical engineering at The University of Akron. In this course, methods of modeling a system's dynamics and describing a system's response in both time and frequency domains are taught. It is found that it is more difficult for students to understand the transfer function representation of a system than to understand the Ordinary Differential Equation (ODE) representation of the same system. Also, students have a much harder time understanding frequency domain analysis than understanding time domain analysis. These difficulties are due to the fact that both transfer function representation of a system and frequency domain analysis are less intuitively related to students' experience with dynamic systems. If some experiments can be developed to intuitively demonstrate these hard-to-learn topics, the teaching quality of this course will be dramatically improved. Recent advances in smart materials [1, 2, 3, 4] make it possible to develop a single setup to demonstrate these experiments. These experiments, once deployed, can bridge the gap between abstract concepts and students' intuition during the teaching of SDR.

Smart materials are used to build the experiment setup. Smart materials refer to the materials that are "responsive." Often the response is the conversion of one form of energy into another in useful quantities. For example, piezoelectric ceramic materials will generate voltage when subjected to strains. Commonly used smart materials include piezoelectric ceramics[1, 2, 3, 4], shape memory alloy [5], magneto-rheological or MR fluids [6], electro-rheological or ER fluids [7], and fiber Bragg Grating optics [8].

Piezoceramic material will be used in this experiment as a sensor to detect and as an actuator to cause structural vibration. Piezoceramic material possesses the property of piezoelectricity, which describes the phenomenon of generating an electric charge in a material when subjected to a mechanical stress (direct effect), and conversely, generating a mechanical strain in response to an applied electric field. This property prepares piezoceramic materials being able to function as both sensors and actuators. The advantages of pieziceramic include high efficiency, no moving parts, fast response, and being compact. A commonly used piezoceramic is the Lead zirconate titanate (PZT), which has a strong piezoeffect. PZT can be fabricated into different shapes to meet specific geometric requirements. PZT patches are often used as both sensors and actuators, which can be integrated into structures. PZT actuation strain can be on the order of 1000 $\mu$strain. Within the linear range, PZT actuators produce strains that are proportional to the applied electric field/voltage. These features make them attractive for dynamic applications.

It has been demonstrated that classroom experimental demonstrations can increase the effectiveness of students' learning.[9] The goal of this project is to develop simple but effective experiments for classroom demonstration for the course of System Dynamic and Response by taking the advantage of smart materials. The dynamic system is a cantilevered flexible beam with bonded PZT sensor and actuators. By using the PZT material, the flexible beam, the sensor, and the actuators are integrated into a single system. This setup is multi-purposed and it can be used to demonstrate several experiments. Though the flexible beam has multiple modes, its first mode is dominant and it can vibrate only at its first mode. When the beam vibrates only at its first mode, it can be modeled by a second order system using a transfer function. By identifying its damping ratio and

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natural frequency, the transfer function representing the first modal dynamics can be identified. This demonstration will help students to intuitively understand transfer function representation of a dynamic system. Another important demonstration is the prediction and observation of a resonance of a dynamic system. The flexible beam can be easily excited at frequencies near its modal frequencies and exhibits resonance. This can help students to understand the effect of frequency of an input signal to a dynamic system. This demonstration will intuitively introduce students to frequency domain analysis. In addition, Bode diagram, which is a key component for frequency domain analysis, can be visualized by this experimental setup. The Bode diagram of the flexible beam with multi-modes can be obtained in advance through system identification. This Bode diagram can be instructed along with a demonstration of flexible beam's vibration with varying input frequency. With changing frequency of the input sinusoidal signal sent to the PZT actuator, change in magnitude and phase angle of the signal generated by the PZT sensor can be observed and will be used to compare with the prediction from the Bode diagram. The demonstration will help students to better understand Bode diagram and analyze a dynamic system in frequency domain.

This experimental setup has been built and integrated into SDR as a tool for classroom demonstrations. It is found that these demonstrations help to bridge the gap between theory and intuition during students' learning process. In addition, these demonstrations have motivated students to further pursue studies in smart structures through senior design projects.

## Background Information about Piezoelectric Ceramic Materials

Piezoelectric material refers to the substances that have the following unique property: an electric charge is produced when a mechanical stress is applied, and conversely a mechanical deformation results from the application of an electric field. The piezoelectric effect is formed in crystals that have no center of symmetry such as quartz and Rochelle salt. An important group of piezoelectric polycrystalline ceramics are ferroelectric materials with the perovskite crystal structure such as barium titanate and lead zirconate titanate (PZT). Ferroelectric ceramics become piezoelectric when poled. Lead zirconate titanate ceramics (PZT) and their modifications are solid solutions of lead titanate and lead zirconate.

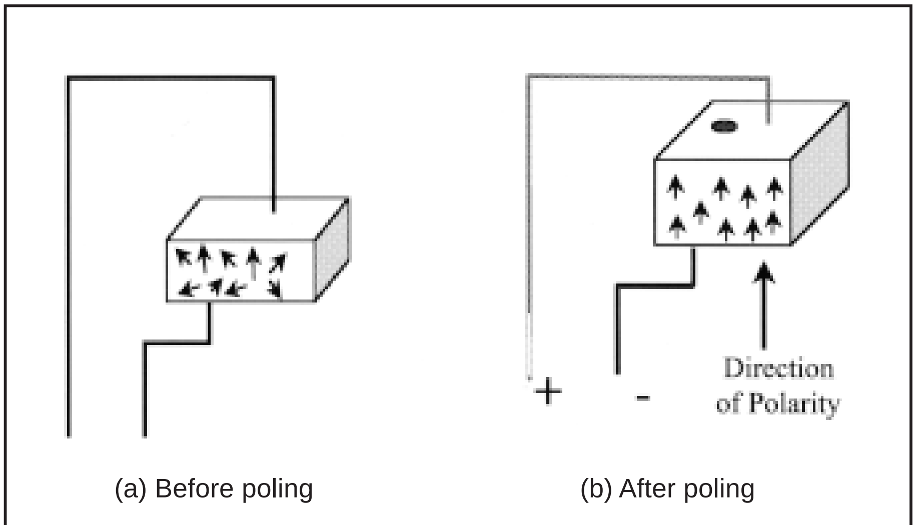


**Figure 1. Comparison of PZT elements before and after poling**

Charge separation between the positive and negative ions is the reason for electric dipole behavior. Groups of dipoles with parallel orientation are called Weiss domains. The Weiss domains are randomly oriented in the raw PZT material (shown in Figure 1(a)), before the poling treatment has been finished. For this purpose, an electric field (> 2000 V/mm) is applied to the (heated) piezo ceramics. With the field applied, the material expands along the axis of the field and contracts perpendicular to that axis. The electric dipoles align and roughly stay in alignment upon cooling (shown in Figure 1(b)). The material now has a polarization, which can be degraded by exceeding the mechanical, thermal and electrical limits of the material. As a result, there is a distortion that causes growth in the dimensions aligned with the field and a contraction along the axis normal to the electric field.

PZT is one of the most commonly used piezoceramics and will be adopted in this research in the form of patches. Figure 2 illustrates the application of the PZT patch to bend a cantilevered beam structure. As shown in the figure, the PZT patch is permanently attached to the beam. When a voltage is applied to the PZT patch, it expands laterally (Figure 2(a)) and bends the beam upwards, as

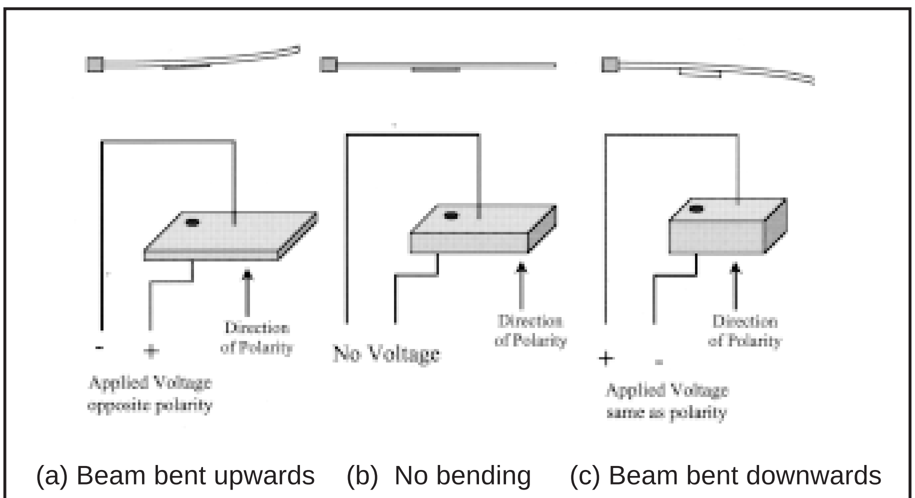


**Figure 2 Piezoceramic Patch as an Actuator**

compare to Figure 2(b) when no voltage is applied. Now the polarity of the applied voltage is reversed, and the PZT patch shrinks laterally and bends the beam downwards (Figure 2(c)). These are examples of motor or actuator action, the conversion of electrical energy into mechanical energy. Finally, if an alternating voltage is applied to the electrodes, the cylinder will grow and shrink at the same frequency as that of the applied voltage. This will cause the beam to vibrate.

On the other hand, the PZT patches can be used as sensors to detect strain changes. When the beam is bent upwards by an external force, the PZT patch is stretched and the voltage across the electrodes will have opposite polarity to the poling voltage (Figure 3(a)). When no load is applied, the output voltage from the PZT patch is zero (Figure 3(b)). When it is forced to elongate along the poling direction, the output voltage will have the same polarity as the poling voltage (Figure 3(c)). These are examples of generator action, the conversion of mechanical energy into electrical energy. Generator action can be found in cigarette and gas lighters, gramophone pick-ups, accelerometers, hydrophones and microphones.

## Experimental Setup

A schematic of the equipment setup is shown in Figure 4. A cantilevered flexible aluminum beam is used as an object to study a system's dynamics and response. The beam has a PZT sensor and a PZT actuator on each side. The aluminum beam is clamped such that its length is parallel to the supporting table below it. This allowed the bending to be strictly in the horizontal plane. The beam simulates vibration of a large flexible solar array of a spacecraft. When the beam vibrates, the sensor will generate a voltage signal and this signal is sent to the data acquisition system and also to the oscilloscope for visualization. On the other side, if a sinusoidal signal is sent to the power amplifier, the amplified signal can drive the flexible beam to vibrate. If the signal is properly designed, it can suppress existing vibrations. 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

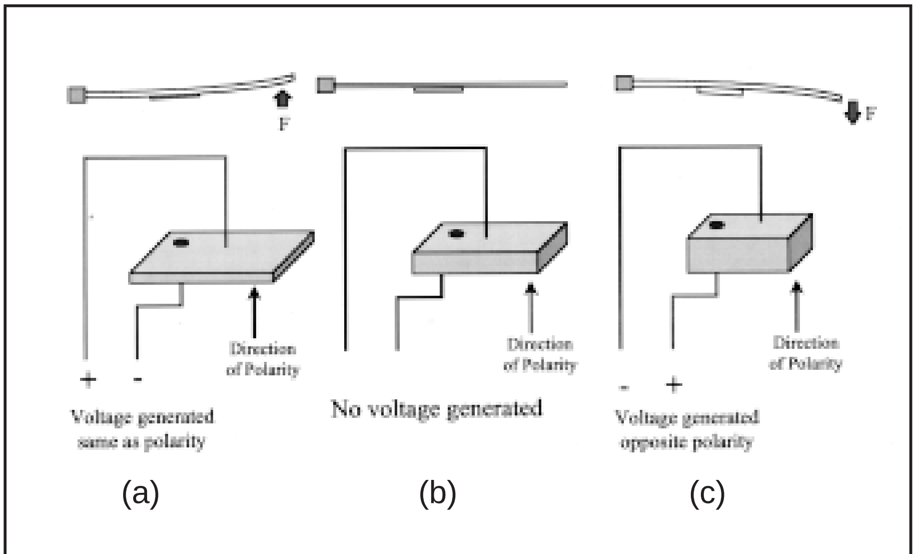


**Figure 3. Piezoceramic Patch as a Sensor**

sense and to react to vibrations. With recent advances in piezo technology, both the piezo patches and the power amplifiers are commercially available at competitive prices. The beam is designed so that the first mode is dominant and far away from its second mode. When the beam vibrates at this first mode, its dynamics can be approximated by a second order linear system.

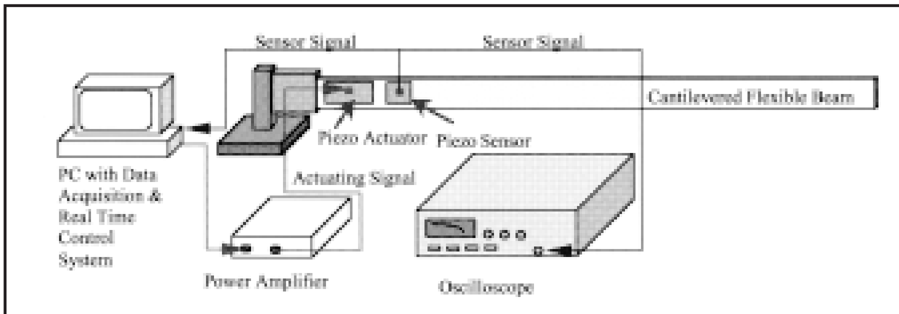


**Figure 4. Cantilevered flexible Beam with Piezo Sensor and Actuators**

The setup described in Figure 4 has been built and Figure 5 shows the completed apparatus. The apparatus uses a flexible aluminum beam with a length of 736.6 mm, a height of 53.1 mm, and a thickness of 53.1 mm. Two PZT patches are used as actuators and one PZT patch is used as a sensor. A dSPACE data acquisition system along with a host PC is used to record and displace experimental data. A function generator (shown in Figure 5) is used to create a sinusoidal input to the system and an oscilloscope is also used to displace experimental data. All components are cart-based and can be easily wheeled into a classroom for demonstrations. The important modal parameters of the flexible beam used in this project are

| Mode | Frequency (Hz) | Frequency (rad/second) | Damping Ratio |
|---|---|---|---|
| 1 | 1.6069 | 10.0965 | 0.013 |
| 2 | 9.73 | 61.1354 | 0.0066 |
| 3 | 26.8 | 168.3894 | 0.0069 |

**Table1. Modal information about the flexible beam**

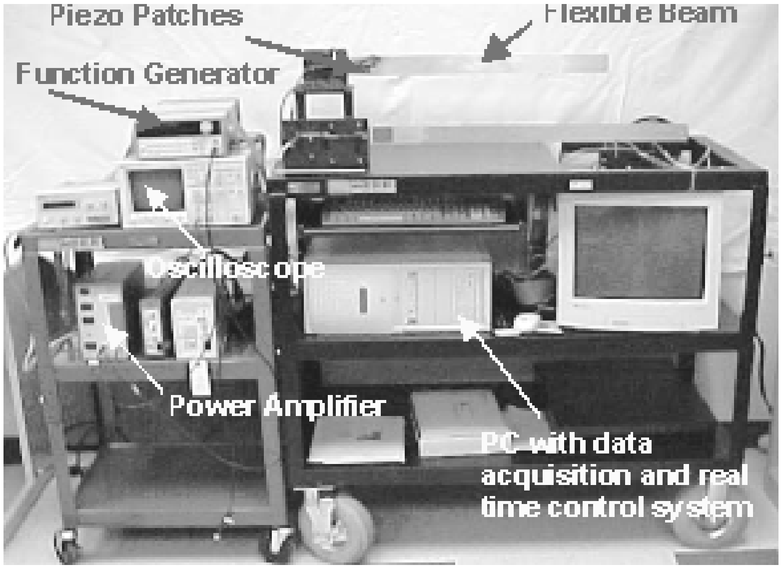


**Figure 5. The flexible beam setup which can be brought to classroom**

shown in the Table 1.

Though flexible beam experiments are common, conventional flexible beam experiments employ external actuators such as shakers. A shaker often weights several pounds and costs several hundreds of dollars. On the other hand, the PZT actuator used in this experiment weights .28oz and costs less than one hundred dollars. Most importantly, the PZT actuator can be surface-bonded to the beam and become an integrated part of beam and can cause the cantilevered beam to vibrate without an external vibrating source.

## Integration with Teaching of System Dynamics and Response (SDR)

The smart flexible beam experimental setup has been integrated with teaching of the System Dynamics and Response (SDR) course through classroom demonstrations. Several demonstrations can be performed to illustrate abstract concepts and improve the quality of teaching. The detailed information about the demonstrations is presented as follows:

### 1) Identify the transfer function of a dynamic system

This demonstration is developed to help student to understand representation of a linear dynamic system using a transfer function. For a second order linear system, the characteristic equation of its transfer function can be described as

$$s^2 + 2\zeta\omega_n s + \omega_n^2 = 0 \qquad (1)$$

where $\zeta$ is the damping ratio and $\omega_n$ is the undamped natural frequency. The characteristic equation of this second order system can be identified by estimating these two parameters.

When the flexible beam vibrates at its dominant first mode, its modal vibration can be approximated by a second order system and its dynamics can be described by eq.(1). To start the demonstration, the flexible beam is manually bent away from its equilibrium position and then released. This action results in vibration of the beam at its first mode. The PZT sensor at the root beam records the strain information which indicates the level of vibrations of the beam. The time history of vibration information can be used to estimate the natural frequency and damping ratio of the system and to establish its transfer function. Shown in Figure 6 is an example of the data when the beam vibrates at its first mode. The $x_1$ represents the magnitude of the first peak and $x_n$ represents that of the nth peak.

If 32 cycles ($n$=32) is chosen, it can be easily determined from Figure 6 that $x_1$ =6.3 (at $t_1$ =0.365 second) and $x_n$ =0.60(at $t_n$ =19.66 second). By using the log decrement formula,

$$\zeta = \frac{\frac{1}{n-1}\left(\ln\frac{x_1}{x_n}\right)}{\sqrt{4\pi^2 + \left[\frac{1}{n-1}\left(\ln\frac{x_1}{x_n}\right)\right]^2}} \qquad (2)$$

the damping ratio $\zeta$ can be calculated. The observed oscillation frequency corresponds to the damped natural frequency $\omega_d$, which can be found by using

$$\omega_d = 2\pi\frac{n-1}{t_n - t_1} \qquad (3)$$

and the undamped natural frequency $\omega_n$ and the resonant frequency $\omega_r$ can be calculated using

$$\omega_n = \frac{\omega_d}{\sqrt{\left(1-\zeta^2\right)}} \qquad (4)$$

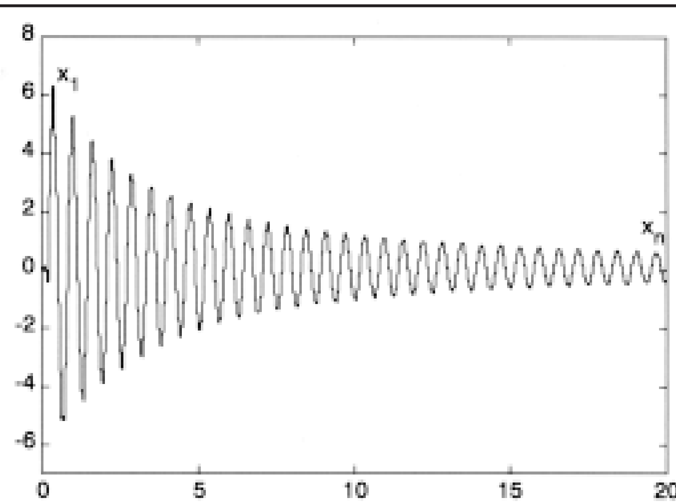


**Figure 6 Free response of the flexible beam vibration at its 1st mode**

The results are , $\zeta$=0.0121,$\omega_d$=1.6066Hz and $\omega_n$=1.6068Hz. Indeed, the values of $\omega_d$ and $\omega_n$ are very close due to the fact that the damping ratio of the system is very small. Now the characteristic equation of the system is identified.

In summary, this experimental demonstration helps students to 1) understand responses of a dynamic system, 2) understand transfer function representation of a dynamic system, 3) understand the characteristic equation of a dynamic system, 4) understand concepts of the damping ratio and the natural frequency, 5) learn how to estimate the damping ratio and the natural frequency, and 6) learn how to identify the characteristic equation.

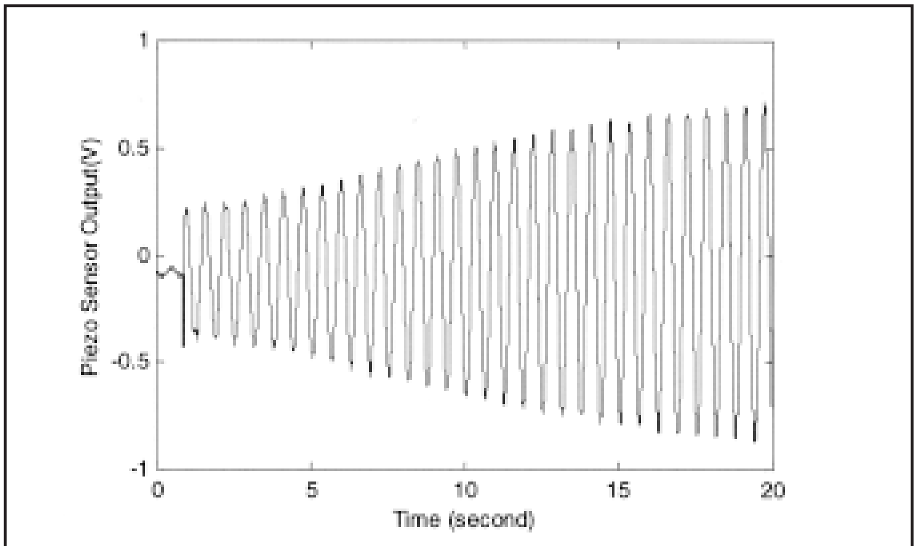


**Figure 7 Resonance of the flexible beam near its first modal frequency**

## 2) Predict and observe resonance of a dynamic system

Resonance must be considered during analysis and control design of a dynamic system with low damping ratio. Resonance of a mechanical system is often destructive. The flexible beam with PZT actuator offers unique demonstrations of resonance. The integrated PZT actuator makes it part of the system and no external actuator is needed. Unlike a motor with unbalanced mass, the PZT actuator can have various input frequencies while keeping magnitude of the input signal constant. The PZT actuator has a high bandwidth and a quick response. Also the PZT material has a long life cycle when operating at low frequency range. All these features make the flexible beam setup appropriate to demonstrate resonance of a dynamic system. If the magnitude of the driving signal to the PZT actuator is chosen properly (generally less than 50V), resonance of the flexible beam can be observed without damaging the system.

Utilizing the first modal frequency and the associated damping ratio, the first resonance frequency of the beam can be calculated.

$$\omega_r = \omega_n \sqrt{\left(1 - 2\zeta^2\right)}$$

It is found that $\omega_r$ =1.6068 Hz. During the demonstration, the flexible beam is excited at this frequency and Figure 7 gives the experimental result. The beam starts vibrating violently with an increasing magnitude. The vibration decreases when the input frequency is tuned away from .

The same demonstration can be conducted at its second resonant frequency and the experimental result is shown in Figure 8.

In summary, this experimental demonstration helps students to 1) learn how to calculate the resonance frequency and 2) visualize the effect of the resonance of a system.

## 3) Understand Bode Diagram

The Bode diagram is a very useful way to represent frequency response characteristics of a linear dynamic system. A Bode diagram consists of two graphs: one is a plot of the logarithm of the magnitude of a sinusoidal transfer function, and the other is a plot of the phase angle. As compared to time-domain response of a system, a Bode diagram is less intuitive for students to understand during instruction of frequency response of a system. The flexible beam setup can assist instruction of the Bode diagram. While keeping magnitude constant, we can vary the frequency of the input sinusoidal signal sent to the PZT actuator to test the frequency response of the flexible beam. The response can be picked up by the PZT sensor. Utilizing the dSPACE real time data acquisition system, the magnitude and phase angle of both input signal and the

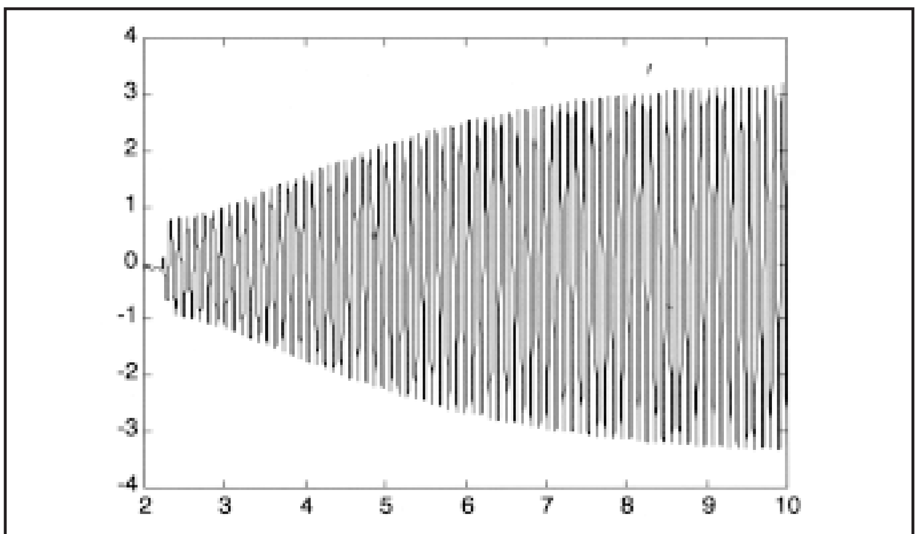


**Figure 8. Resonance of the flexible beam near its second modal frequency**

sensor output can be recorded and compared. The results can help students to understand the Bode diagram of this flexible beam system.

If the first three modes of the flexible beam are taken into considerations, the transfer function of the system can be modeled by

$$\frac{Vs(s)}{Va(s)} = \frac{518.4\,s^4 + 594.2\,s^3 + 2.634e006\,s^2 + 7.284e005\,s + 2.813e008}{s^6 + 3.393\,s^5 + 3.22e004\,s^4 + 4.031e004\,s^3 + 1.093e008\,s^2 + 3.104e007\,s + 1.08e010}$$

where Vs(s) is the Laplace transform of the sensor voltage and Va(s) is the Laplace transform of the voltage sent to the actuator. The zero-pole locations of the system are shown in Figure 9 and Figure 10 presents a close-up of the first and second zeros and poles. Please note that poles are represented by small crosses and zeros are represented by small circles. The Bode diagram of this system is shown in Figure 11. Both the magnitude and phase delay slowly increases when the input frequency is tuned towards the first modal frequency. This observation is consistent with the Bode diagram. When the input frequency approaches closely to the first modal frequency, dramatic increase in magnitude and phase delay is observed. The magnitude and phase delay peak at the first resonant frequency that is almost identical to the first modal frequency due to a small value of its associated damping ratio. As the input frequency increases and moves away from the first modal frequency, the output magnitude decreases and reaches a minimum at the frequency associated with the nearby zero. Meanwhile, the phase delay continues to increase until the input frequency reaches the frequency associated with the nearby zero. With further increase of input frequency, the output voltage changes little

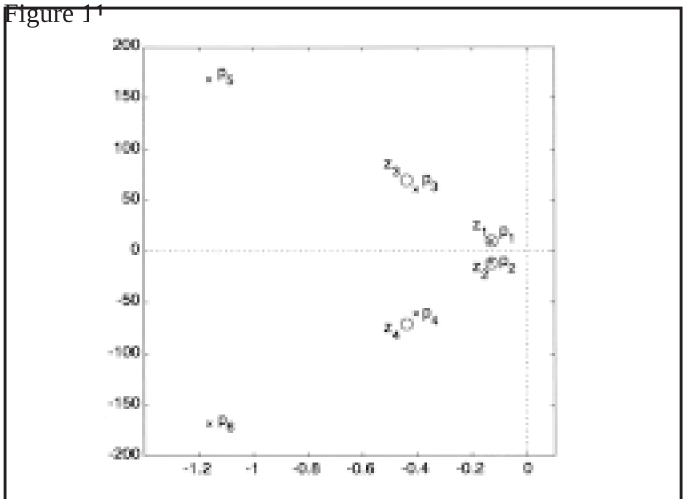


**Figure 9. Zero and pole configuration of the flexible beam**

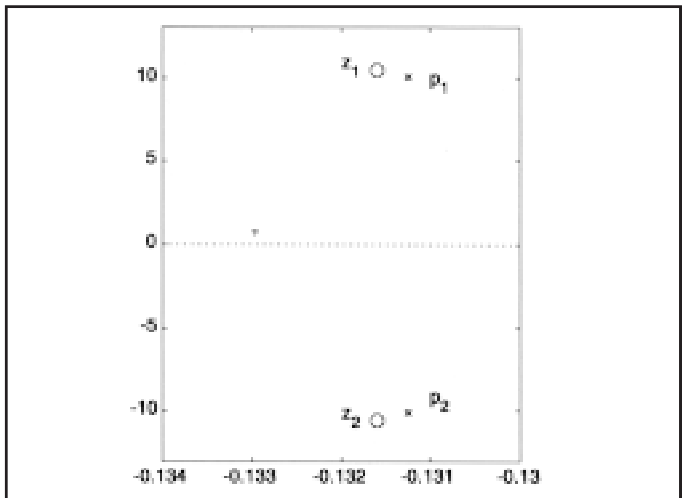


**Figure 10. Close-up of the first and second zeros and poles**

During the classroom demonstration, a signal generator is connected to the voltage amplifier for the PZT actuator. The signal generator is set to generate a sinusoidal signal with a constant peak-to-peak voltage. The frequency of the sine wave can be controlled to demonstrate the effect of input frequency on a system's response, and the observed response will be compared with the Bode diagram in Figure 11. The demonstration starts with a frequency lower than the first modal frequency (1.6 Hz or 10.05 rad/s). During this range, the output signal has small values of magnitude and the phase delay.

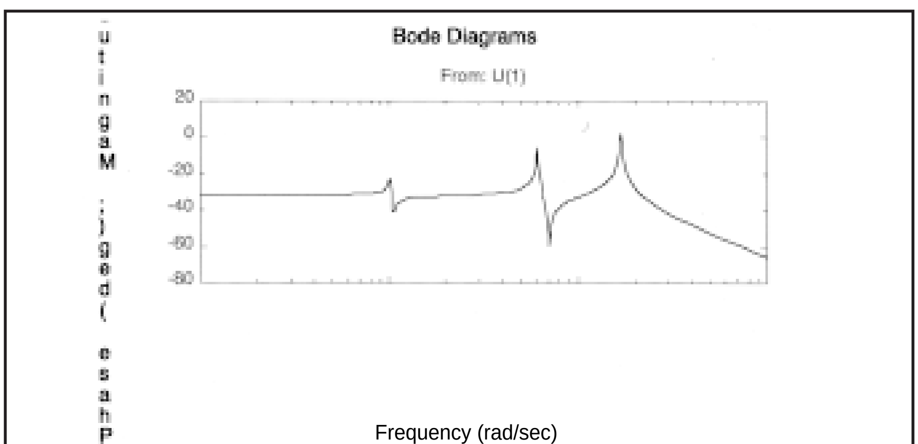


**Figure 11. Bode diagram of the flexible beam**

and the phase delay is reduced to zero due the phase lead introduced by the pair of complex zeros.

When the input frequency is increased near the second modal frequency, the phenomenon observed near the first mode is repeated. For frequency above the third mode, the observation does not map the Bode diagram accurately since the higher modes have been truncated in the system model.

In summary, this experimental demonstration helps students to 1) understand the importance of frequency domain analysis, 2) interpret the Bode diagram of a dynamic system, and 3) locate zeros and poles of a system through a Bode diagram.

### 4) Additional Benefits

The following summarizes additional benefits of using the smart material experimental setup for classroom demonstrations.

· Expose dynamics and control of flexible structures and smart sensor and actuators to mechanical engineering students and increase undergraduate education diversity.

·Prepare students for the course of Control System Design.

· Motivate perspective mechanical engineering students to pursue further study in the directions of control of dynamic systems and smart structures. Since the introduction of these demonstrations in SDR in the Spring 2000, there were eight students (out of 43) who chose their senior design projects in smart structures under the advice of the authors.

### 5) Survey Results

At the end of the semester, students were asked to fill out an anonymous survey which included ranking of the effectiveness of the smart material experiment. The result is shown in Figure 12. It is clear that most students thought the experiment was effective to some degree. Followings are some students' comments:

· It is good to use equipment and makes the material more interesting to learn.

· Both theory and practical examples should be taught and combined, which this class did.

· Demos help. I am a visual person. The beam demo was excellent.

· Being able to actually see the beam that is vibrating helps to understand the concepts behind it.

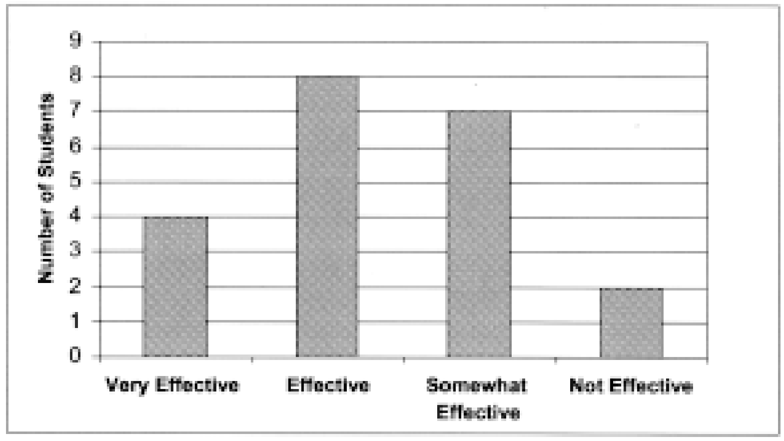


**Figure 12. Students' Evaluation of the Effectiveness of the Smart Material Experiment**

These comments clearly show these classroom demonstrations are effective and help to bridge the gap between theory and intuition during a student's learning process.

## Conclusions

This paper describes several simple but effective classroom demonstrations using a smart material experimental setup funded by a 1999 University of Akron Summer Teaching Grant. This experimental setup takes advantage of recent development in smart materials and smart structures and it offers multiple demonstrations. These experimental demonstrations have been integrated with teaching of System Dynamics and Response (SDR). Positive feedback from the students' survey shows these demonstrations are effective and these demonstrations help to bridge the gap between theory and intuition during the students' learning process. In addition, these demonstrations have helped to motivated students to further pursue studies in smart structures through senior design projects. The future work will involve further detailed evaluations of the effectiveness of each smart materials experimental demonstration in SDR.

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