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Combining Course Flipping and a Low-Cost Experiment to Teach Frequency Response

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Abstract

This work-in-progress paper investigates the effectiveness of a course module on frequency response/Bode plots in a junior-level dynamic systems and control course. The module includes flipped lectures, a random Bode problem generator, and an experiment using a 3D printed beam. The effectiveness of the module is assessed through pre and post surveys, student comments on the course evaluations, and by comparing scores on a specific final exam question between two offerings of the course.

Introduction

In a recent offering of a dynamic systems and control course, students seem disinterested in an early lecture on finding the response of a mass/spring/damper system to a sinusoidal input. An in-class survey revealed that the lack of interest was coming from not understanding the importance of sinusoidal inputs. The students agreed that mass/spring/damper systems are both practical and prevalent in the real world. However, roughly half of the students see sinusoidal inputs as no more important than any other input to a dynamic system. The survey results from early in the course are shown in Figures 1-5. The first two questions sought to assess whether or not the students really were disinterested in the lecture. Questions 3 & 4 asked whether or not students believed mass/spring/damper systems are important. Question 5 asks about the importance of sinusoidal inputs for system identification.

Literature Review

This paper touches on two topics that are being discussed in the literature: flipped instruction and low-cost experiments in dynamic systems and controls courses. Course flipping refers to having students watch a lecture video or make some other effort to learn the material before coming to class so that class time can be used for some form of active learning such as working through example problems or performing experiments. Online video streaming and other technological advances have made course flipping easier and many instructors have

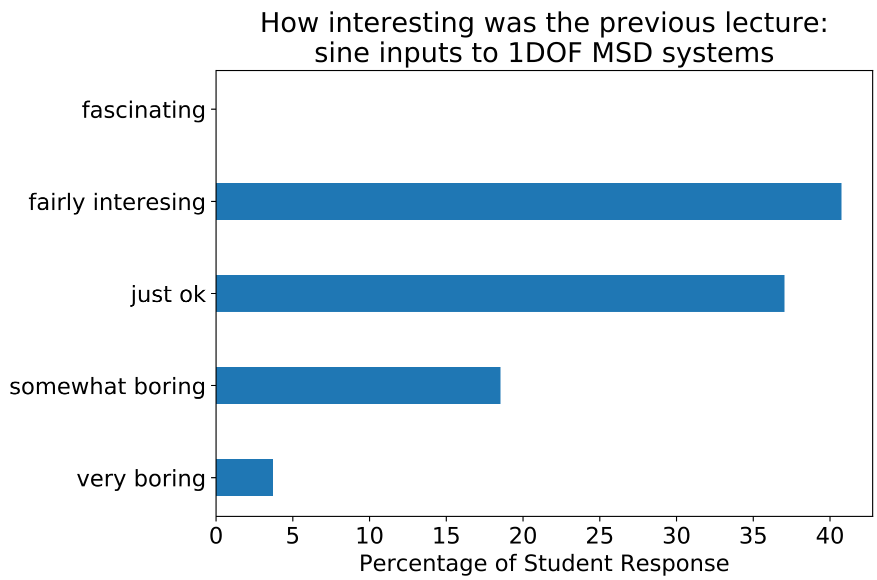

Figure 1: Question 1 from a survey early in the semester probing why students seemed disinterested in the sinusoidal response of a mass/spring/damper system.

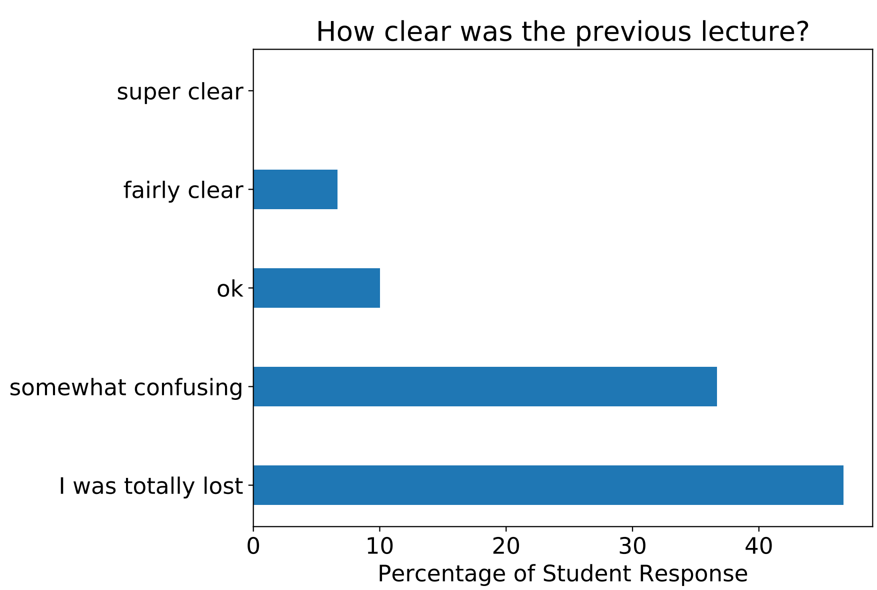

Figure 2: Question 2 from a survey early in the semester probing why students seemed disinterested in the sinusoidal response of a mass/spring/damper system.

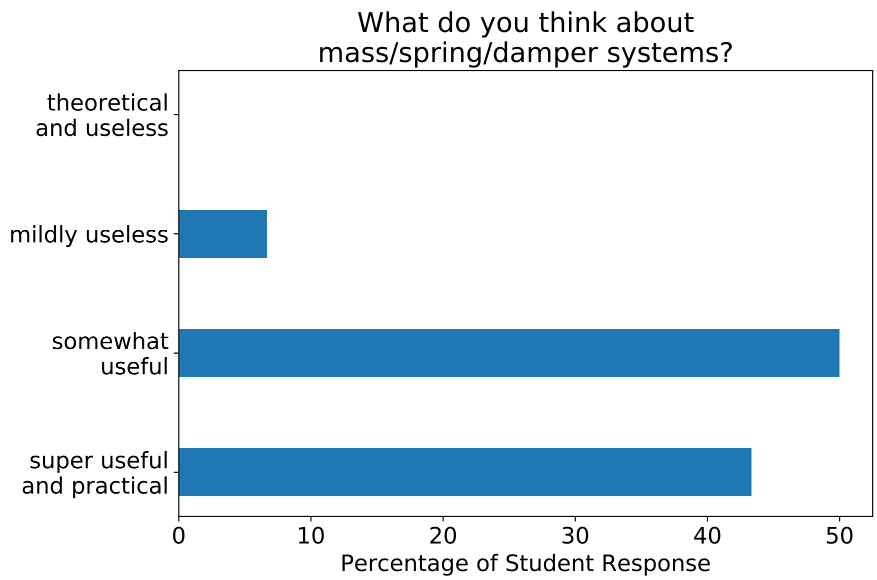

Figure 3: Question 3 from a survey early in the semester probing why students seemed disinterested in the sinusoidal response of a mass/spring/damper system.

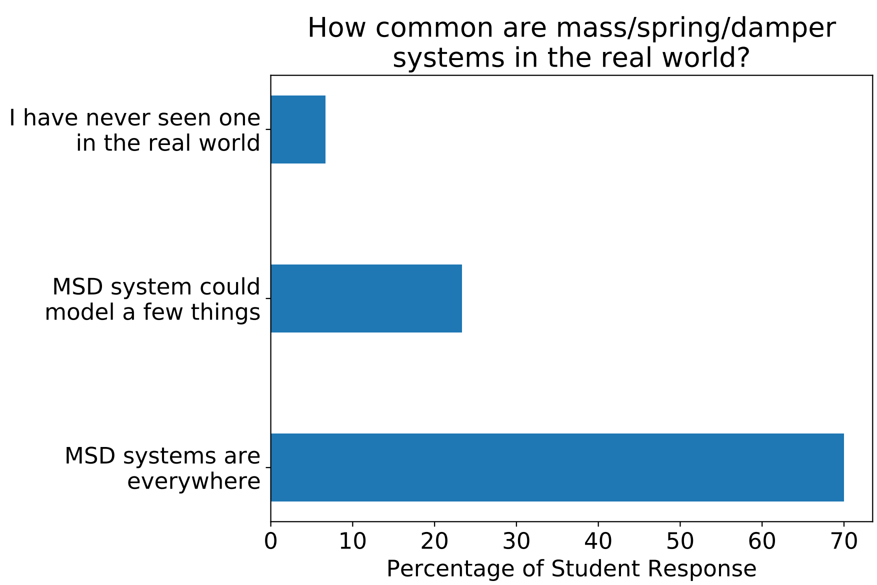

Figure 4: Question 4 from a survey early in the semester probing why students seemed disinterested in the sinusoidal response of a mass/spring/damper system.

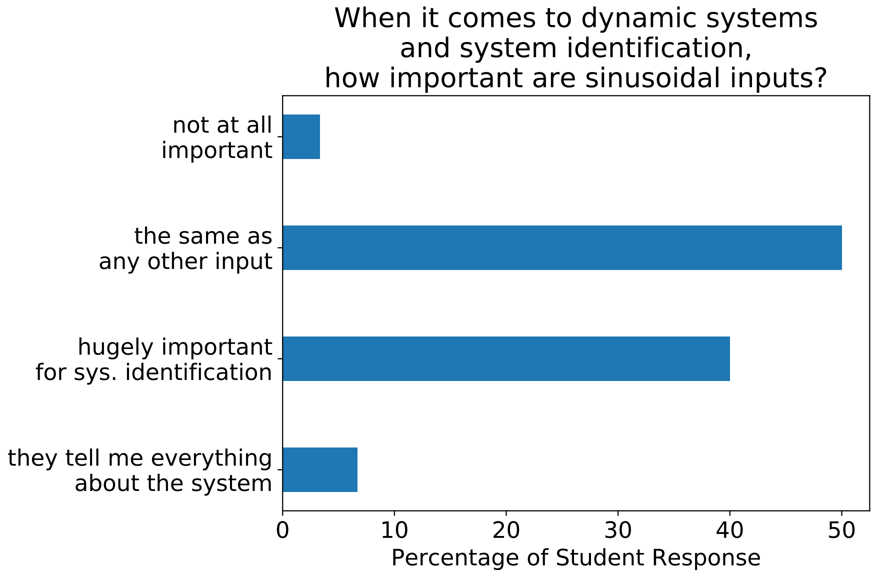

Figure 5: Question 5 from a survey early in the semester probing why students seemed disinterested in the sinusoidal response of a mass/spring/damper system. This question was later repeated after the frequency response module to see how students appreciation of sinusoidal inputs had changed.

tried various approaches to it [1]. Course flipping has been used in many engineering courses [2] and has been specifically applied to feedback controls course [3].

Dynamic systems and controls courses can be mathematically intensive, intimidating, and abstract. Physical experiments can increase student learning by making the concepts seem more concrete and tangible [4, 5, 6, 7, 8]. However, some approaches to real-time feedback control experiments require custom hardware and/or software and can be quite expensive. The cost of maintaining on-campus feedback control laboratories has sparked an interested in low-cost experiments that can potentially be student owned [9, 10, 11].

A very promising approach combines flipped instruction with student owned experiments using an Arduino microcontroller and Matlab [12].

The work presented in this paper uses an Arduino microcontroller combined with Python so that the hardware is inexpensive and all of the software is free.

Pedagogical Question

Primarily, this paper seeks to answer the question "How effective was the frequency response/Bode learning module?". The Bode module had several student learning objectives: Students will

- know how to sketch Bode plots by hand
- analyze Bode plots to find transfer functions

- be able to find the response of a system to a sinusoidal input from a Bode plot
- appreciate the importance of sinusoidal inputs in generating experimental Bode plots
- know how to experimentally generate a Bode plot for system identification purposes

Learning Module Content

The learning module consisted of three components:

1. A series of flipped lecture videos posted to YouTube
2. A random Bode problem generator written in Python
3. A demonstration of a low-cost experimental frequency response system consisting of a 3D printed beam and a low-cost accelerometer

The topics for the flip lectures included the following:

- Introduction to Frequency Response/Bode Plots for Dynamic Systems
- Bode Part 1: Sketching
- Bode Part 2: Sketching Examples
- Bode Part 3: Generating Bode Plots in Python
- Bode Part 4: Interpreting Bode Plots (System ID)
- Bode Part 5: Random Bode Problem Generator
- Bode Part 6: Experiments on a DC Motor + Beam System
- Digital Signal Filtering with Arduino

The playlist for these videos can be found here: https://www.youtube.com/playlist?list=PL5C8qVtFmjvdDiLRgCW2u956zwqG24Z6O.

Additionally, there was one live Q & A session before the exam covering the material from the flipped lectures.

The 3D printed beam and low-cost accelerometer are demonstrated in the video "Bode Part 6". The video shows a swept sine experiment and walks the user through the Python code to generate the Bode plot from the swept sine results.

The random Bode problem generator seeks to intelligently come up with pseudo-random transfer functions that are well-suited for students who are learning Bode plots for the first time. Mainly, this means that the poles and zeros are reasonably well spaced so that they do not essentially cancel each other in ways that would confuse a student who is just learning about Bode plots and frequency response.

The Bode problem generator can be used in two ways. First, it can show the student the transfer function and ask them to sketch the Bode plot. When the student is done with their sketch the program can then genrate the Bode plot for comparison purposes.

Alternatively, the program can show the student the Bode plot and ask them to determine the corresponding transfer function. When the student is done, the program will show them the actual transfer function, allowing them to grade their own work.

Description of the Experimental System

Many dynamic systems and control instructors use a DC motor system in their courses. These systems are generally fairly similar and consists of a DC motor, an encoder, and an H-bridge. Such a system can easily be controlled by an Arduino microcontroller and real-time data can be streamed from the Arduino back to a computer over the USB-to-serial connection. Such a system can be built from off-the-shelf components for less than $100 per student or per lap station. A picture of such a system is shown in Figure 6.

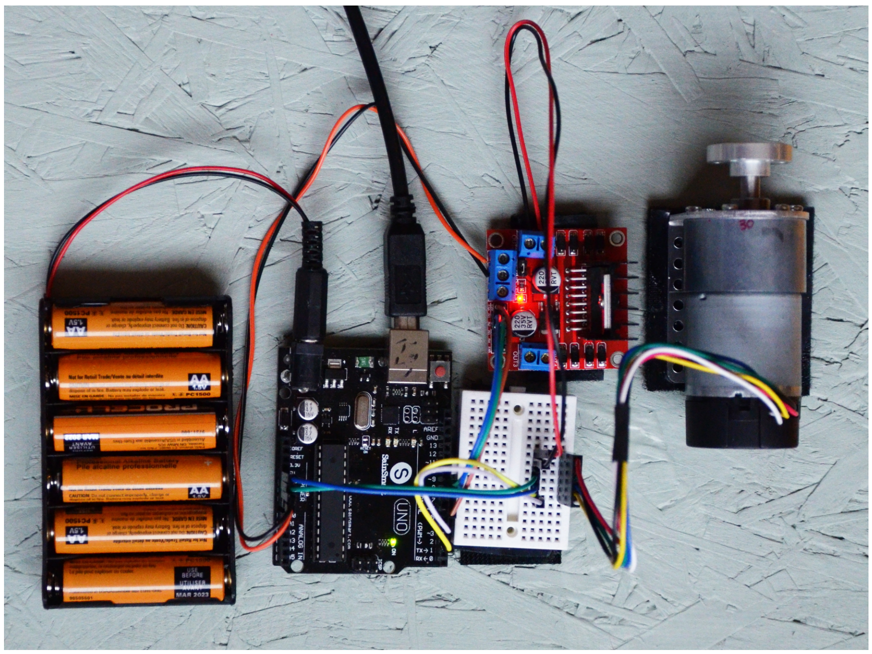

Figure 6: Picture of a DC motor/encoder/H-bridge system used in many dynamic systems and controls courses during an introductory lab experiment.

The 3D printed beam and low-cost accelerometer used in this work attached directly to such a DC motor system. So, if a DC motor position control system is already being used in the course, the Bode plot experiment for the beam cost less than $20. The beam can be 3D printed for a very small price. Small PCBs that contain MEMS accelerometers and associated signal conditioning components can be purchased for $5 to $25.

A picture of the beam mounted on the DC motors is shown in Figure 7. Standoffs for mounting the accelerometer were included in the beam design, as shown in Figure 8. The fact that the beam is made out of a non conductive plastic material reduces the risk of shorting any of the components on the accelerometer board. However, the beam could easily be made out of almost any material.

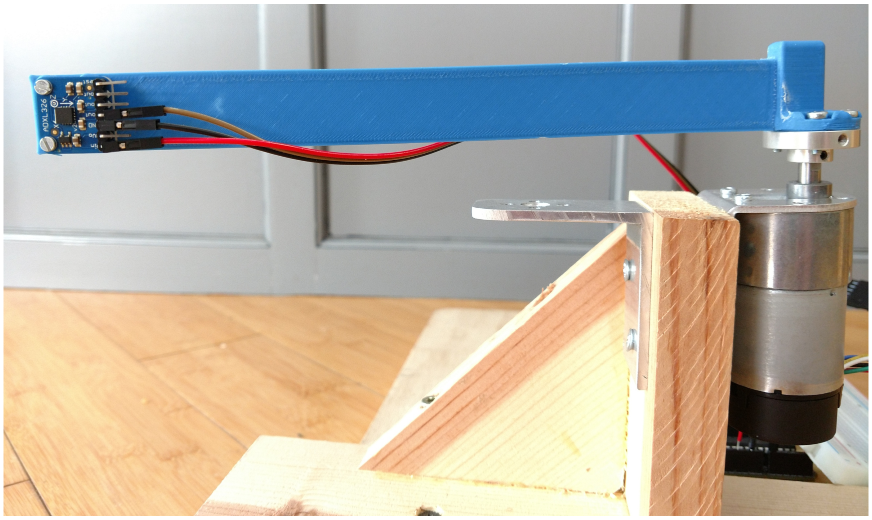

Figure 7: Picture of the 3D printed beam and low-cost accelerometer mounted on the DC motor.

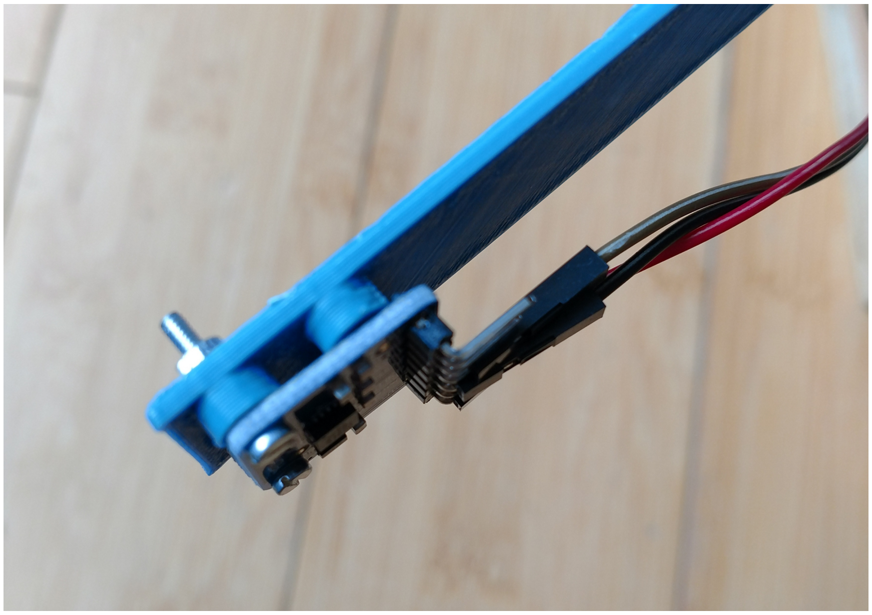

Figure 8: Picture of the accelerometer mounts integrated into the design of the 3D printed beam.

Assessment Approach

The student learning outcomes for the frequency response/Bode learning module were assessed in three ways:

1. Surveys administered before and after the learning module
2. Comments from the standard student evaluations for the course
3. Comparing final exam performance between this year and the previous year when the material was taught in a traditional face-to-face lecture

The survey before the module was mainly trying to measure whether or not students appreciated the importance of sinusoidal inputs for system identification. The post module survey consisted of two multiple-choice questions and two essay questions. The first multiple choice question was the same as that used on the pre module survey to measure the difference in student appreciation of the importance of sinusoidal inputs. The second multiple choice question tried to measure whether or not students understood some of the practical details of running frequency response based system identification experiments. The two essay questions were fairly similar to one another and tried to go deeper in assessing student understanding of how to generate a bode plot from experimental data.

Assessment Results

Figure 9 compares the multiple-choice survey results before and after the learning module for the question concerning the importance of sinusoidal inputs. The module seems to have convinced a reasonable number of the students of the importance of sinusoidal imports in system identification.

Figure 10 shows multiple choice survey results for the post module survey regarding which input is appropriate for experimental Bode plot generation. The correct answer is a swept sine input. This point was not overly emphasized during the learning module but 55% of the students got this question right on the survey.

The students answers to the two essay questions show opportunities for the learning module to be improved. The first question asked the students to list the experimental steps necessary to find a transfer function for a system. The second question explicitly asked the steps necessary to experimentally find the Bode plot for a system. In the author's estimation, some students got the question 1/2 to 3/4 correct. But no one got the questions more than 75% correct. The average scores for these questions would have been very low if this were a test question. The author believes that the responses to the essay questions could have been significantly improved if the students were allowed to run swept sine experiments themselves rather than merely watching a demonstration.

Students in the school of engineering at Grand Valley State University have complained about flipped lectures in the past. The primary complaint is that they should not be required to pay for a course if they are going to have to "teach themselves". Several students explicitly

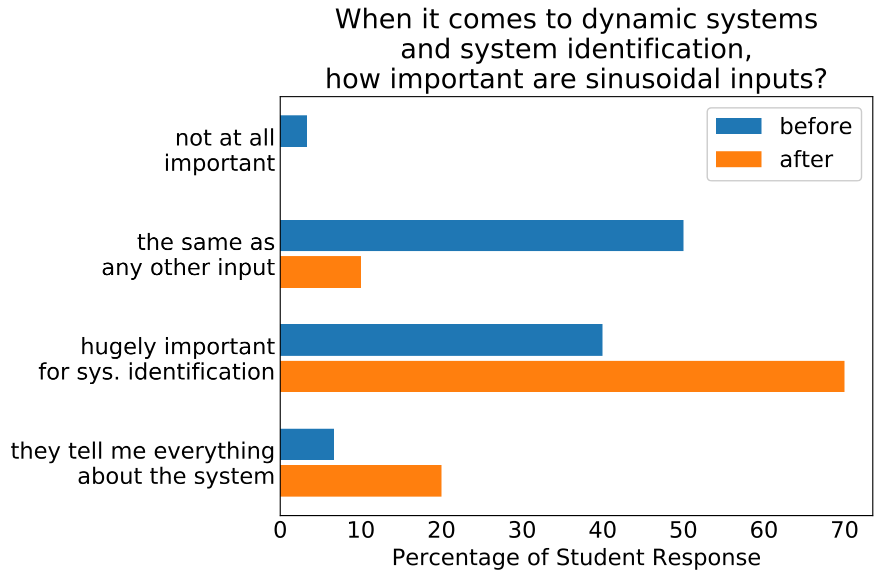

Figure 9: Survey results before and after the frequency response/Bode learning module for a question regarding the importance of sinusoidal inputs

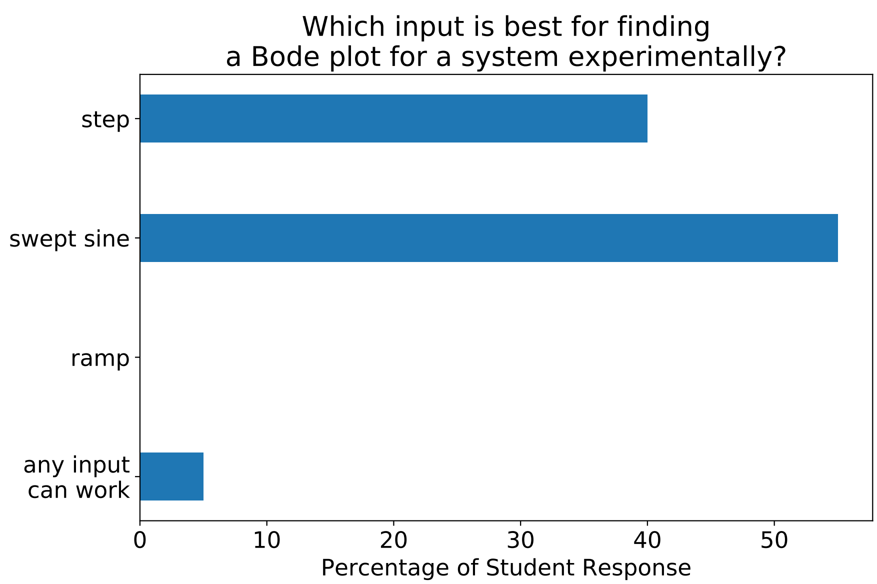

Figure 10: Results from a multiple choice question on a survey administered after the frequency response/Bode learning module. The correct answer is “swept sine”.

mentioned the flipped lectures in their comments on the course evaluation forms. A small number of students seem to like the flipped lectures while the majority of the comments said that flip lectures should not be used in the future for this material.

Even though some of the students did not like the flipped lectures, students in the fall 2017 offering of the course out performed students in the fall 2016 on a very similar final exam question regarding Bode plots and frequency response. During the 2016 offering of the course, the frequency response/Bode material was taught using traditional face-to-face lectures. Figure 11 shows the Bode plot from the 2016 final exam where the question was:

> The Bode plot of a system is shown above. If the system is given an input of $u(t) = 5\sin(4\pi t)$, find the steady-state output.

The 2017 offering of the course asks a very similar question:

> For the system whose Bode plot is shown above, estimate the steady-state response to the input $u(t) = \sin(4\pi t) + \sin(60\pi t)$

And the corresponding Bode plot is shown in Figure 12.

The average for students on the 2016 final exam for this question was 79.8% while the average for the 2017 final exam question was 88.1%.

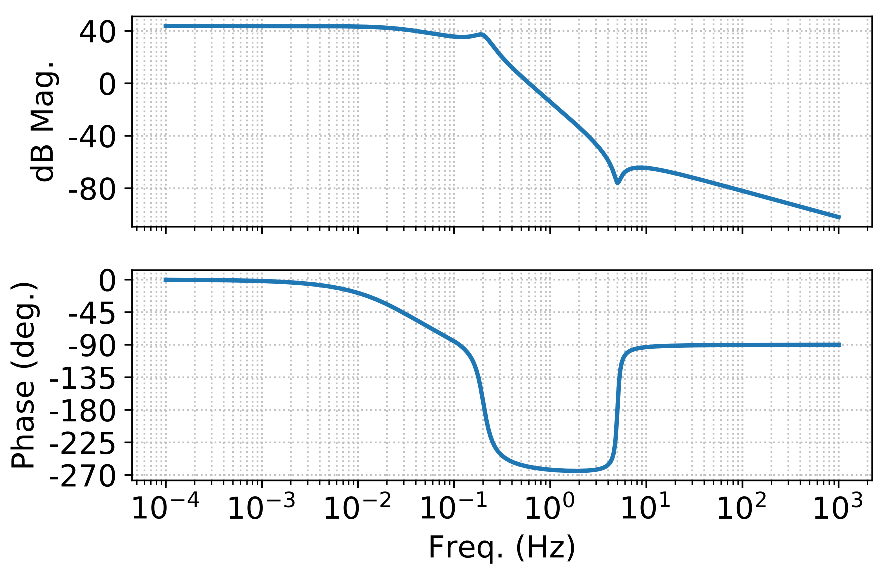

Figure 11: Bode plot for the 2016 final exam question

Conclusions

Overall, the frequency response/Bode learning module seems to have been successful. Despite students complaints regarding flip lectures, the students seem to have learned the material. In fact, the students who watched the flipped lectures scored higher on a very similar final exam question than students in the previous year's course who had face-to-face lectures for

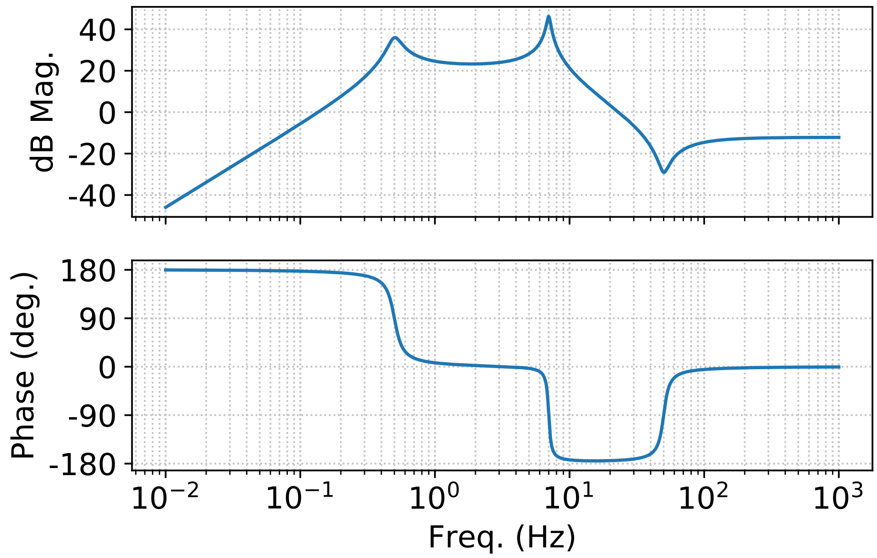

Figure 12: Bode plot for the 2017 final exam question

this material. The 3D printed beam and low cost accelerometer appears to be an excellent way to generate realistic experimental Bode plots at a price that is cheap enough for student owned experiments.

The primary way that this approach could be improved would be to make sure that the students have opportunities to experimentally run frequency response tests themselves.

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