Vibration Suppression Control of 3D Printed Beams

Abstract

Dynamic systems and feedback control courses can be mathematically intensive and seem abstract and theoretical. Physical experiments can make the material more concrete, increasing student interest and deepening understanding. However, there are several challenges associated with performing real-time feedback control experiments. Commercially available experimental systems can be expensive. Faculty who develop their own experiments must balance cost and complexity while creating something the ties into lecture material. This paper presents a novel, low-cost experimental system that deepens students' understanding of system identification and root locus control design. The system consists of a 3D printed beam attached to a DC motor. An Arduino microcontroller is used for real-time feedback control and Python is used for control design and data analysis.

Background and Introduction

Dynamic systems and feedback control courses can seem mathematically intensive and intimidating to students. Developing differential equation models and performing Laplace transform analysis can seem abstract. Physical experiments can help students see how real and practical these courses truly are by allowing students to visualize the response of various systems. Experiments make this abstract material concrete and capture students' interest [1, 2].

However, there are several issues that make it challenging to bring experiments into feedback control and dynamic systems courses. Experimental equipment is often expensive, laboratories take up valuable space, and there can be many practical issues associated with the hardware and software needed to run these kinds of experiments. The plants being used in these experiments need to be well-designed such that they have interesting dynamic behavior without being either too simple or too complex. There is also a balancing act between creating experimental systems that can easily be modeled using transfer functions and the other theoretical tools the students are learning in class while also bringing in practical issues such as friction that students will face in the real world [3]. Additionally, motors with low friction and minimal backlash can be very expensive, so it is difficult to avoid some of these practical issues.

There are other challenges associated with analog-to-digital and digital-to-analog conversion hardware as well as controlling the digital timing of the experiments. Feedback control experiments are usually best performed at hard real-time intervals on the order of milliseconds. In order to accomplish this timing, either specialized hardware and software are needed or a microcontroller needs to be used. There are commercially available solutions to these problems that have been well-recieved by students [4, 5, 6]. However, some of these systems can be quite expensive.

One solution to both the cost of experimental equipment as well as the space requirements for having university-owned laboratories is the growing trend of student-owned experiments. Many educators have presented novel and interesting experiments for dynamic systems and control courses that cost less than an engineering textbook [7, 8, 9, 10].

This paper presents a novel, low-cost dynamic systems and control experiment with interesting dynamics. The project described in this paper was performed using the combination of Python and Arduino microcontrollers, using only free and open source software. The project required students to apply experimental system identification based on Bode plots and root Locus control design to a vibration suppression problem involving a 3D printed beam attached to a DC motor.

Course Description

This project was part of a required junior-level course that teaches dynamic systems modeling and introduces feedback control. The course includes background theory on the Laplace transform, transfer function modeling, and partial fraction expansion. It includes finding transfer functions from first principles for circuits and mass/spring/damper systems. It also includes relating pole locations to various aspects of the step response of underdamped second-order systems. Fixed sine response and Bode plots are introduced both theoretically and experimentally. Root locus control design is taught near the end of the course. Principles of feedback control are integrated throughout the course.

The project was assigned with roughly six weeks remaining in the course. At that point, Bode system identification had already been covered, but root locus control design had not yet been introduced. As a result, the students spent the first week or two experimentally determining the transfer function of the beam/motor system before beginning the control design.

System Description

Figure 1 shows the 3D printed flexible beam mounted on the DC motor. An H-bridge and AA battery pack allow an Arduino microcontroller to drive the motor. The system has one input and two outputs. The input is the PWM voltage command sent to the H-Bridge. The outputs are the encoder that measures the rotation of the DC motor and an accelerometer that measures vibrations at the tip of the beam.

Real-time feedback control experiments are performed using an Arduino microcontroller. The Arduino reads the encoder signals using pin interrupts and communicates with the accelerometer using i^2c (i^2c is serial communication protocol used to connect multiple electronic devices such as microcontrollers). A timer interrupt is used to enforce a 250 Hz digital control frequency. All control calculations are performed in real time on the Arduino. A digital compensator library for the Arduino is used to allow the students to use arbitrary transfer functions in their accelerometer feedback loop. The Arduino prints real-time, delimited data to the serial monitor. This data can be copied and pasted into a text file and loaded into Python or Python can communicate directly with the Arduino using the serial library. Python is used for control design, simulation, data analysis, and plotting.

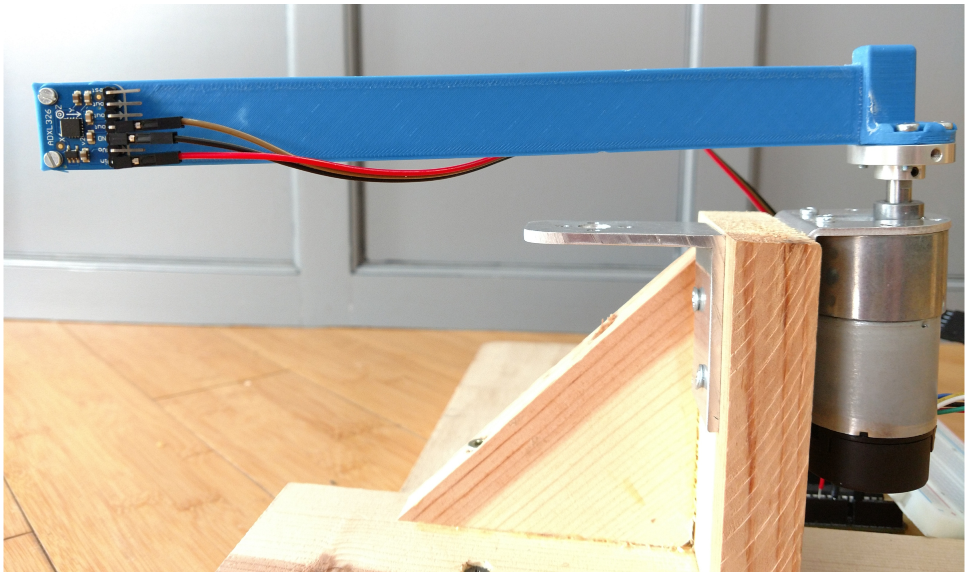


Figure 1: The 3D printed beam attached to a DC motor.

The entire system costs roughly $120, not including the cost of 3D printing. If a DC motor/H-bridge system is already in use in a course, the accelerometer and 3D printed beam are roughly a $10-20 addition. A DC motor/ H-bridge encoder system not including the beam can be assembled for $80-100 and forms a foundation for dynamic systems and control experiments, such as time and frequency domain system identification, deadband, PID tuning, and control design using root locus and Bode techniques.

The project was performed in groups of 2-3 students and each group was given a system like the one shown in Figure 1.

Project Description

The project assignment was to develop a vibration suppression controller to minimize the settling time of both the encoder and accelerometer signals when the system was given a step input in the desired encoder position. The students were given the suggested block diagram shown in Figure 2. Before the students can begin designing the acceleration feedback transfer function $A(s)$, they need a well-tuned PD controller $D(s)$ for the encoder feedback loop as well as a transfer function for acceleration/desired encoder angle, $Accel(s)/U(s)$. Students were able to find this transfer function based on swept sign Bode plots as shown in Figure 3. Note that the transfer function includes the first and second modes of vibration for the flexible beam. The system identification portion of this project could be used in a dynamic systems course that did not include feedback.

Once the system identification was complete, students were ready to start designing the acceleration feedback transfer function. One fairly common problem with experimental feedback control projects is that they often deteriorate into PID tuning. Because the accelerometer is being used in feedback, PID tuning really does not work on this system. Students are forced to ask themselves what form the compensator for accelerometer feedback should take and this ultimately drives them into root locus design. The students learn to identify closed-loop pole locations that would potentially

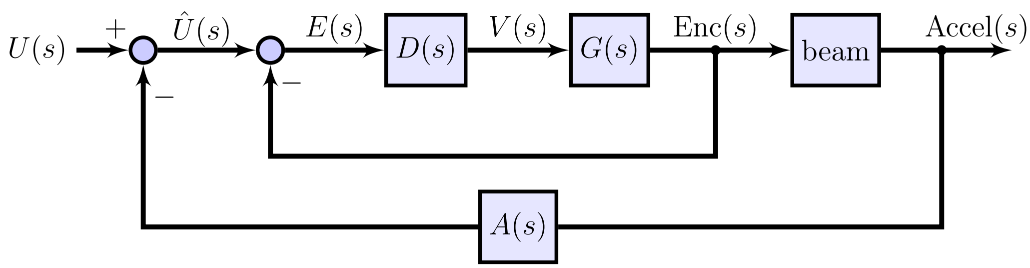


Figure 2: Block diagram for the vibration suppression system with two feedback loops.

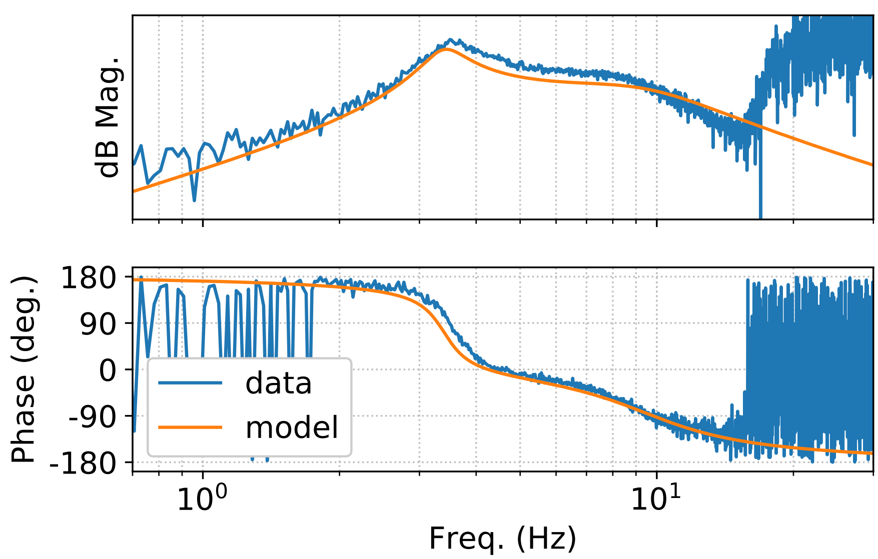


Figure 3: Experimental and model Bode plots for $Accel(s)/U(s)$, where $Accel$ refers to the acceleration at the tip of the beam and U is the desired joint angle for the DC motor.

improve the system response and to evaluate the open-loop transfer function at those locations to determine whether phase needs to be added or subtracted. This process guides students toward using a low-pass filter on the accelerometer feedback signal. This conclusion falls out of the root locus analysis without requiring any intuition on the students part regarding why accelerometer signals would need a low-pass filter. An example root locus for a low-pass filter design for the acceleration feedback transfer function $A(s)$ is shown in Figure 4.

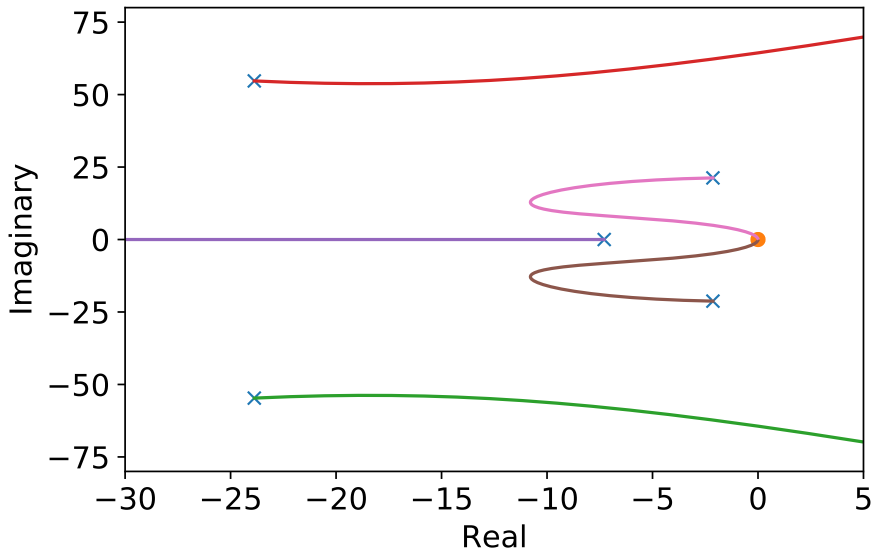


Figure 4: Root locus for a low pass filter design for the acceleration feedback transfer fuction $A(s)$.

The project ended with a competition to see which team could get the lowest settling time. If acceleration feedback is not used, rapid motion of the motor can cause tip vibrations that take 2-4 seconds to die out. All of the teams successfully designed a control system that led to an accelerometer settling time of less than 0.8 seconds. The winning settling time was 0.42 seconds. Figure 5 shows the acceleration step response with and without vibration suppression control.

Assessment

All of the teams succeeded in lowering the settling time through accelerometer feedback control, so in that sense the project was successful. In order to dig deeper into how much the students learned from the project, two final exam questions were specifically designed to assess concepts that should have been reinforced by the project.

The first final exam question related to the project was a multiple choice question where students were asked to pair pole locations with step responses. Here is the question as it was presented on the final exam:

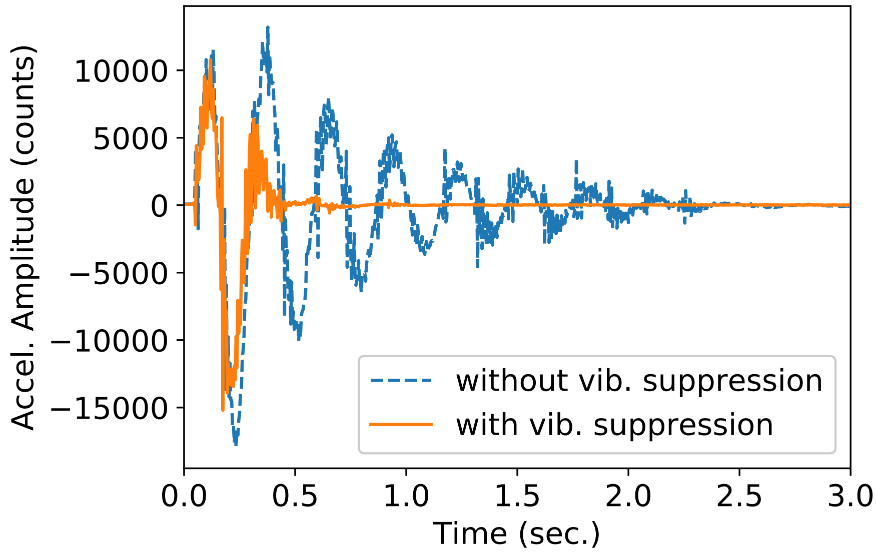
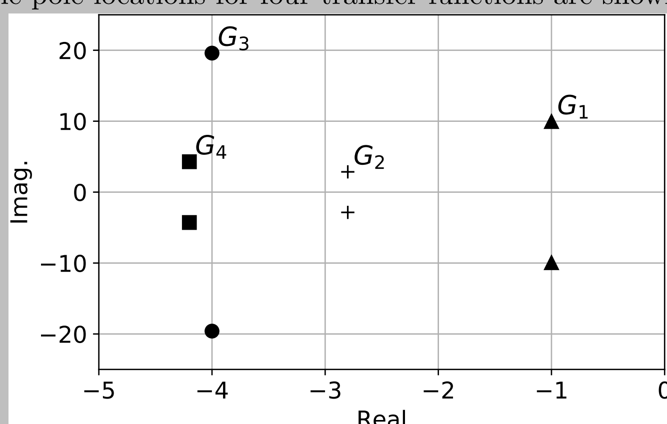
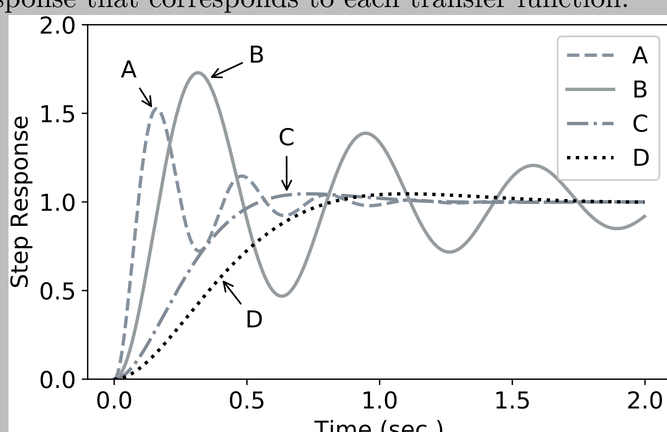


Figure 5: The acceleration at the tip of the beam with and without vibration suppression control when the motor is given a step input.

2. (10 points) The pole locations for four transfer functions are shown below



Find the step response that corresponds to each transfer function:



G_1: __________

G_2: __________

G_3: __________

G_4: __________

The average score on this final exam question was 6.4 out of 10. Out of 33 students taking the exam, 17 of them (51.5%) got this problem completely correct. As a point of comparison, a similar question was given on the final exam in 2016. The students in that year performed system identification on 3D printed beams but did not do the vibration suppression design. The average score in 2016 was 6.9 out of 10, but only 8 out of 20 students (40%) got the problem completely correct.

The second final exam question related to the project required the students to do root locus design using only a calculator (Python was not allowed on the final exam). Here is the question as it was presented on the final exam:

> 5. (20 points) Design a feedback control system for the plant
>
> $$G(s) = \frac{s+2}{s^2+2s+10}$$
>
> that places the dominant closed-loop poles at $-5 \pm 3j$. You do not have to find a numeric value for the gain K, but you must find numeric values for all other parameters. Describe the steps needed to find K in as much detail as you can.

The average score on this question was 13.5 out of 20 or 67.6%. Out of 33 students taking the final exam, 9 of them (27.3%) got this question completely correct. In addition to the 9 who got the problem completely correct, one student did everything correct expect explaining how to find the final control gain K. Two more students made only minor mistakes. Additionally, 16 out of 33 students correctly found the phase of the plant at the desired pole location and from that information correctly determined that they need to add a pole in their controller in order to cause the root locus to pass through the desired pole location.

Conclusions

While the assessment results are somewhat inconclusive, the project still seemed to benefit the course. Students were able to apply what they had learned regarding Bode system identification and root locus control design to an experimental system. Students were able to accurately model and simulate the system using transfer functions and the linear system analysis tools they had learned in lecture. Students seemed to enjoy the project and find it challenging. All of the teams were able to improve the settling time of the system through accelerometer feedback.

References

[1] Bernstein, D., “Enhancing undergraduate control education,” *Control Systems Magazine, IEEE*, Vol. 19, No. 5, oct 1999, pp. 40 –43.

[2] Bernstein, D., “Control experiments and what I learned from them: a personal journey,” *Control Systems Magazine, IEEE*, Vol. 18, No. 2, apr 1998, pp. 81–88.

[3] Schinstock, D., Smith, S., and White, W. N., “Does inexpensive hardware obfuscate simple experiments for control systems laboratories?” *American Control Conference (ACC), 2017*, IEEE, 2017, pp. 5355–5360.

[4] Shiakolas, P. and Piyabongkarn, D., "Development of a Real-Time Digital Control System with a Hardware-in-the-Loop Magnetic Levitation Device for Reinforcement of Controls Education," *IEEE Transactions on Education*, Vol. 46, No. 1, 2003, pp. 79–87.

[5] Kamis, Z., Topcu, E., and Yuksel, I., "Computer-Aided Automatic Control Education With a Real-Time Development System," *Computer Applications in Engineering Education*, Vol. 13, No. 3, 2005, pp. 181–191.

[6] Salzmann, C., Gillet, D., and Huguenin, P., "Introduction to Real-time Control using LabVIEW with an Application to Distance Learning," *Int. J. of Engineering Education*, Vol. 16, No. 5, 2000, pp. 372–384.

[7] Reck, R. M., "BYOE: Affordable and Portable Laboratory Kit for Controls Courses," *122nd ASEE Annual Conference and Exposition, 2015*, Paper ID: 13467.

[8] Schinstock, D., McGahee, K., and Smith, S., "Engaging students in control systems using a balancing robot in a mechatronics course," *2016 American Control Conference (ACC)*, IEEE, 2016, pp. 6658–6663.

[9] Bay, C. J. and Rasmussen, B. P., "Exploring controls education: A re-configurable ball and plate platform kit," *2016 American Control Conference (ACC)*, IEEE, 2016, pp. 6652–6657.

[10] Hill, R., "Hardware-based activities for flipping the system dynamics and control curriculum," *American Control Conference (ACC), 2015*, IEEE, 2015, pp. 2777–2782.