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3D-PRINTED LABORATORY EQUIPMENT FOR VIBRATIONS AND CONTROL THEORY COURSES: PENDULUM, CANTILEVER BEAM, AND RECTILINEAR SYSTEM

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ABSTRACT

Learning by doing has proven to have numerous advantages over traditionally taught courses in which the instructor teaches the topic while students remain passive learners with little engagement. Although laboratories give hands-on opportunities for undergraduate mechanical engineering students, they have to wait for a semester for the lab course for instance the prerequisite of the vibrations and control laboratory is the mechanical vibrations course. Since the nature of the dynamics branch consisted of dynamics, vibrations, and control theory courses are highly mathematical, students struggle comprehending the introduced topic and relate the theory to its real-world application area. Furthermore, it's almost impossible for an instructor to bring the existing educational laboratory equipment to the class since they are bulky and heavy. The advents in manufacturing technology such as additive manufacturing bring us more opportunities to build complex systems new materials.

This study presents the design, development, and implementation of low-cost, 3D printed vibratory mechanisms to be utilized in mechanical vibrations, control theory courses along with their associated laboratories. A pendulum, cantilever beam integrated with springs, and a rectilinear system consisted of two sliding carts, translational springs, and a scotch yoke mechanism are designed. The main parts of the mechanisms are 3D printed using polylactic acid (PLA), polyethylene terephthalate glycol (PETG), and thermoplastic polyurethane (TPU).

Keywords: portable laboratory equipment design, 3D printing, vibrations and control theory courses

NOMENCLATURE

ω_n	natural frequency
k	spring constant
c	damping constant
δ	logarithmic decrement
ζ	damping ratio

1. INTRODUCTION

Learning by doing has proven to have numerous advantages over traditionally taught courses in which the instructor teaches the topic while students remain passive learners with little engagement [1-3]. Dynamics is one of the main branches of mechanical engineering consisted of dynamics, mechanical vibrations, and introduction to control theory which primarily focuses on the derivation of the mathematical model of vibratory mechanisms, systems, and machines to further analyze their response to any given input. The vast majority of mechanical engineering undergraduate students struggle in representing the machines/mechanisms by their equivalent mass-spring-damper model, deriving the equations of motion and linking the theory to real-world applications [4]. Students' deep conceptual understanding and higher-order skills in these courses can be enhanced if the traditional lectures are taught with demonstrations of the fundamental topic using portable laboratory equipment [5,6].

Laboratories are an important part of the undergraduate engineering curriculum. Dewey construed the laboratory equipment as one of the mechanics of learning if the variance is a factor [7]. Observing the effect of a single parameter variance on the system response helps students better comprehend the subject [8]. However, in many cases, the educational laboratory equipment employed in the vibrations and control laboratories are heavy, bulky, and high-priced making it difficult to accommodate multi stations. Consequently, students have to wait for a long time for their turn to conduct experiments. Besides, the turn-key educational equipment is embedded with their software to record and export data thereby students also don't discern the signal flow and connections from the sensors to the data acquisition cards. This is one of the major problems of the equipment utilized in the vibrations and control laboratories.

Several portable laboratory equipment has been developed for the electrical engineering laboratories. A low-cost kit was developed and provided to the control laboratory students [9]. Tekes et al developed a portable, 2 DOF compliant parallel-arm mechanism consisted of fixed-free flexible beams attached to a slider. The mechanism was actuated by a linear actuator and the positions of the carts were acquired through laser displacement sensors [5]. Although the mechanism was portable, the total cost was around $1200 for one setup. In our previous work, we designed and developed three portable and low-cost vibratory mechanisms [10]. A compliant vibratory mechanism to demonstrate resonation and vibration isolation, a driver car seat model comprised of a cart suspended by springs mounted on a driver belt to simulate deviations on the road and a rectilinear system to demonstrate fundamentals of free vibrations.

In this study, we developed three novel, open-source, and low-cost portable vibratory equipment to be utilized in mechanical vibrations and control theory courses along with their associated laboratories. The first mechanism consisted of a cantilever beam, support, and multiple springs, which is created to demonstrate fundamentals of free vibrations, finding the lumped mass-spring-damper model, and validating theory through experimental data collected from ADXL accelerometers, Arduino and Matlab. The beam is designed in a way enabling multiple spring attachments on different locations between the support and the beam. Additional masses can also be attached to the beam to change the effective mass. All parts of the mechanism including the helical springs are 3D printed in polylactic acid (PLA). The second mechanism is a 3D printed pendulum, comprised of a mounting for the encoder, pendulum rod, and magnets to change the tip load. The mechanism can be used to study system identification using the theory, and free-response data from the encoder and Matlab. The third system is a rectilinear setup incorporating a rail, two sliders, dc motor, springs, two ADXL accelerometers, connecting rod, and scotch yoke mechanism. While the main parts of the mechanism are 3D printed in PLA, horizontal springs are 3D printed in thermoplastic polyethylene (TPU) to provide required compression and tension during motion. The total mass of the carts can be changed by adding loads on each and springs possessing various stiffnesses are designed to modify the properties of the system. The rectilinear system can be used to study free and forced vibrations, system identification, and trajectory control by designing a PID controller. The superiorities of the proposed mechanisms over educational turn-key equipment are their low cost and lightweight and also since the designs are open source, any of the parts can be 3D printed if broken or damaged due to overuse.

The paper is outlined as follows. The designs are presented in Section 2 and the implementation of the laboratory equipment in the mechanical vibrations course, control theory, and their associated laboratories are discussed in Section 3. Future plans on studying student learning is provided in Section 4 and Concluding remarks are summarized in the conclusion.

2. DESIGN OF PORTABLE and 3D-PRINTED LABORATORY EQUIPMENT

This section presents the design and development of three novel laboratory equipment to be utilized in the machine dynamics and vibrations, systems dynamics and control theory, and vibrations and control laboratories.

2.1 Pendulum with a tip load

The designed pendulum consists of a rod, support, and a rotary encoder (Taiss/Incremental Rotary Encoder) to record the angular position of the pendulum as shown in Figure 1. Data is recorded through Arduino using jumper wires. All parts of the pendulum are 3D printed in PLA. The tip of the rod has holes to place circular magnets. This enables to attach as many magnets as possible together to change the tip load. The pendulum can be attached to any table with a maximum edge thickness of 10 cm. The bolts are used to tighten for edges less than 10 cm. Students can attach as many magnets as they prefer to the tip of the rod.

FIGURE 1: Cad model, separate parts and images of different assemblies

2.2 Cantilever beam attached to springs

Finding the equivalent mass and stiffness is one of the principal topics taught in the mechanical vibrations courses. A common problem to demonstrate the topic is a cantilever beam attached to several springs from different points with a load at its tip. Students struggle in getting to the equations of motion, representing the system using its equivalent values, and visualizing the vibrations in the vertical direction. To alleviate this problem, we designed a vibratory setup comprised of a cantilever beam, support for the beam, a case to hold the springs, and translational springs as shown in Fig. 2. The torsional springs can be connected between the cantilever beam and the case or between the base and the cantilever beam. The holes on

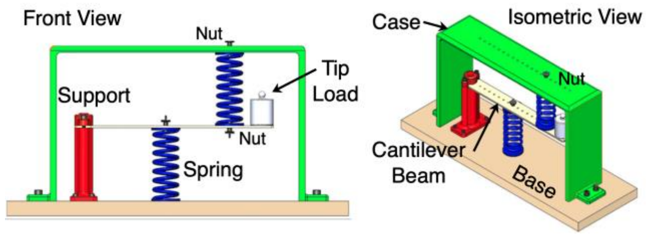

FIGURE 2: Cad model of the cantilever beam

the case enable us to mount the springs using nuts. Although the springs can be attached to the case using nuts, the double-sided tape can be used as an alternative.

All parts of the mechanism are 3D printed. While the case, pendulum, and support are 3D printed in PLA, the springs are 3D printed in TPU to provide more flexibility thereby more elongation as shown in Figure 3. The beam can hold up to 3 springs connected at any point.

To record data from the experimental setup, an ADXL 335 accelerometer and Arduino are utilized. Students can acquire data through Arduino or external NI DAQ using either Matlab or NI Signal Express.

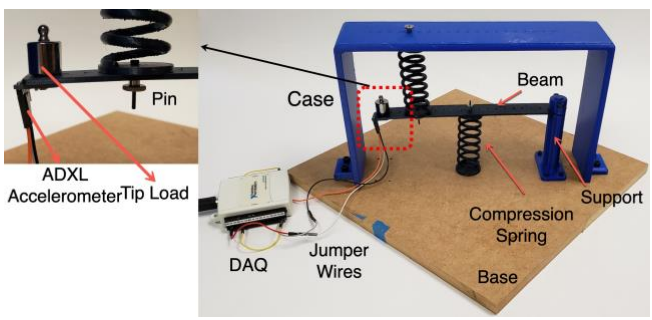

FIGURE 3: Experimental setup of the cantilever beam

2.3 2-DOF Rectilinear Setup

Turn-key rectilinear systems have been favorably utilized in the vibrations and control laboratories. The proposed rectilinear system consists of a scotch yoke mechanism, cylindrical rods, cart rail system, three carts with magnets to hold weights, cart lockers, three springs, two accelerometers, a DC motor, L298N motor driver, and an Arduino as shown in Figure 4. The

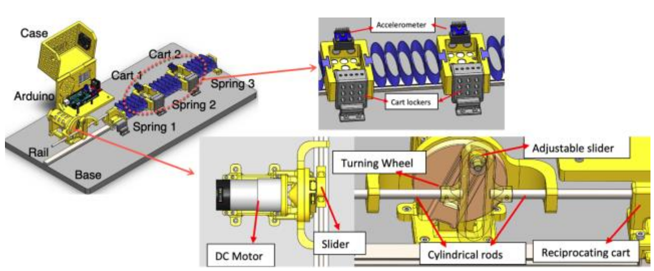

FIGURE 4: CAD model of the rectilinear mechanism

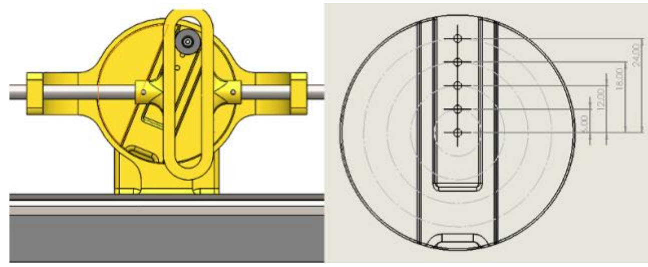

FIGURE 5: Adjustable slider configuration

translational compression springs are 3d printed using PETG filament while the electronic casing, charts, scotch yoke mechanism, and cart lockers are printed using PLA filament.

The scotch yoke mechanism is used to convert the rotational motion of the dc motor shaft into linear motion through a turning wheel and a slider. Two cylindrical rods are attached to the slider to constrain the motion along the horizontal direction. As the motor rotates the turning wheel the slider moves back and forth thereby pushing and pulling the reciprocating cart. The reciprocating cart translates the motion through the 3D printed springs to the sliding carts 1 and 2. The scotch yoke mechanism has an adjustable slider to control the stroke as illustrated in Figures 4 and 5. The adjustable slider has a bearing on it to confine the rod during the reciprocating motion. Furthermore, the current configuration has a stroke of 24 mm which can be adjusted between 6mm, 12mm, 18mm, and 24mm.

Each sliding cart has an accelerometer for data collection as well as magnets in order to add variations of weights. Besides, each cart has its own cart locker to restrict the motion thus creating a SDOF system. Also, the reciprocating cart can be locked if the user is only conducting free vibrations and not forced vibrations as seen in the complete setup shown in Fig. 6.

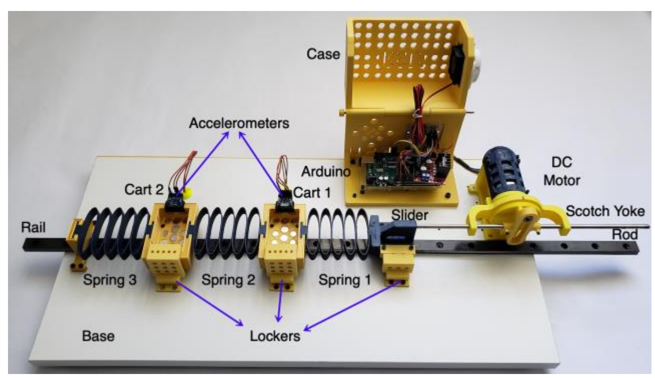

FIGURE 6: Experimental setup of the rectilinear system

3. EXPERIMENTAL DESIGN

The proposed portable laboratory mechanisms are designed to demonstrate the fundamentals of vibrations by illustrating the concepts taught in introductory level mechanical vibrations and control theory courses. 3D printed laboratory equipment can be taken to the classroom, provided to the students by building several of the same setups as a class activity, homework, or laboratory assignment. Assuming that a student has a strong knowledge of statics and dynamics which are the pre-requisites of the vibrations and control theory courses, the learning objectives that can be covered using the proposed laboratory equipment are: (1) derive the equation of motion of SDOF and 2 DOF vibratory mechanisms, (2) calculate the damping and stiffness from experimental data using logarithmic decrement method for underdamped systems, and (3) find the free and forced response of systems using Matlab Simulink. This would allow students to apply their knowledge to an applied engineering problem. An ancient proverb well describes the need for hands-on learning as "*Tell me, and I forget; Show me, and I remember; Involve me, and I understand*" [11,12].

Faculty can adopt the 3D printed laboratory equipment in their vibrations and control laboratory or mechanical vibrations and control theory courses and create new assignments. The activities can start with preliminary questions as a class discussion: (1) What is the difference between undamped and damped natural frequency?, (2) How can you calculate the natural frequency of a vibratory system using experimental data?, and (3) List possible ways/methods to determine the damping of a system. Each activity can be followed up with critical thinking questions such as (1) Does damping affect the natural frequency of a system? Why or why not?, (2) What are the three most important concepts that you have learned in this lab? And (3) What are three applications (in addition to a pendulum system) where you might use these concepts?

In this section, we present the modeling and system identification of the vibratory mechanisms as a case study.

Beam with Springs System Identification. The sketch of the mechanism along with the simplified and lumped mass-spring-damper model is depicted in Figure 2. The equivalent stiffness of the beam can be obtained using the energy stored in the springs including the stiffness of the cantilever beam

$$U_{total} = \frac{1}{2}k_1 x_1^2 + \frac{1}{2}k_2 x_2^2 + \frac{1}{2}k_b x_b^2 = \frac{1}{2}k_{eq}x^2 \quad (1)$$

$$k_{eq} = k_1\left(\frac{L_1}{L}\right)^2 + k_2\left(\frac{L_2}{L}\right)^2 + k_b \quad (2)$$

where k_1 *and* k_2 are the stiffnesses of the compression springs. If the mass of the cantilever beam is neglected compared to the mass of the tip load (100g), the distances of the springs from the fixed end of the cantilever beam are ($L_1 = 20\ cm, L_2 = 15.4\ cm$) and the length of the cantilever beam is 20 cm. Although the dimensions such as the diameter and the number of turns of the compression can be changed to change the stiffness, we used the identical springs so that $k_1 = k_2 = k$. Since the system is SDOF, the natural frequency $\omega_n = \sqrt{k_{eq}/m_{eq}}$. An ADXL accelerometer is attached to the free end of the cantilever beam (see Fig. 3), the beam is deflected to record free response data as illustrated in Fig. 7. Also, the stiffness of the cantilever beam is

$$k_b = \frac{3EI}{L^3} \quad (3)$$

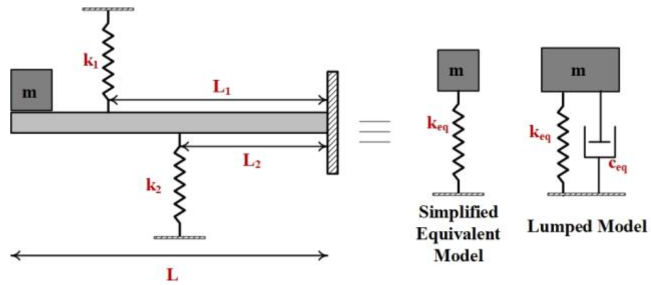

FIGURE 7: Sketch of the cantilever beam with springs and its simplified and lumped model

where k_b is the stiffness of the cantilever beam, E is Young's Modulus (2.1 GPa for PETG), I is the moment of inertia of the cantilever beam ($\frac{bh^3}{12}, h = 0.27\ cm\ and\ b = 2.5\ cm$). Since the natural frequency is obtained as 50.26 rad/sec, the equivalent stiffness is calculated as 252.66 N/m. The stiffness of the cantilever beam is around 12.6 N/m and the spring constant of a single torsional spring is 148 N/m using the equation below

$$k = \left(k_{eq} - k_b\right)\frac{L^2}{L_1^2 + L_2^2} \quad (4)$$

If the two consecutive peaks (X_1, X_2) are read from the free response data shown in Fig. 8, then the logarithmic decrement (δ) and the damping ratio (ζ) can be calculated to obtain the damping constant (c)

$$\delta = \ln\left(\frac{X_1}{X_2}\right) \rightarrow \zeta = \frac{\delta}{4\pi^2 + \delta^2} \rightarrow c = 2m\zeta\omega_n \quad (5)$$

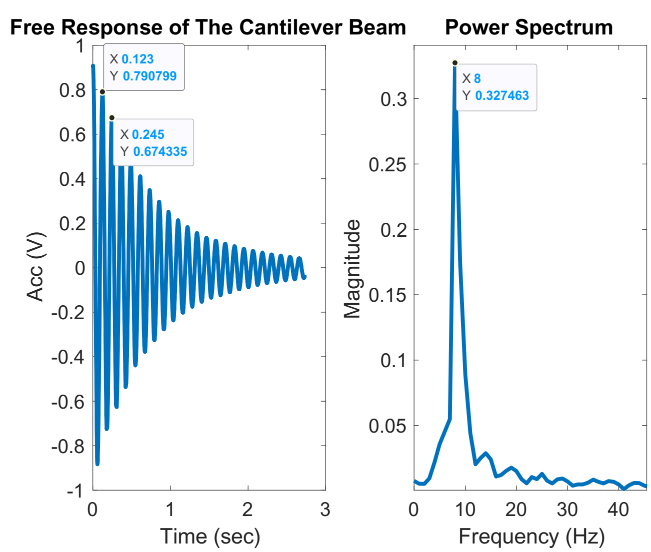

FIGURE 8: Free response data collected from the cantilever beam-2 spring system

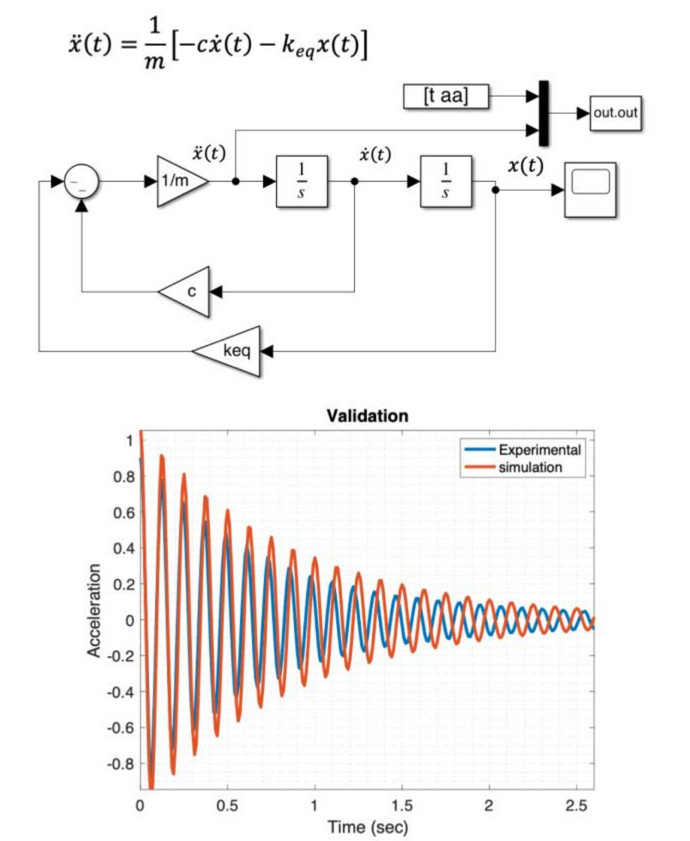

FIGURE 9: Free response data collected from the cantilever beam-2 spring system

The equivalent damping constant is calculated as 0.22 Ns/m. The governing equation of the cantilever beam with the springs is

$$m\ddot{x}(t) + c\dot{x}(t) + k_{eq}x(t) = 0 \tag{6}$$

$$\ddot{x}(t) = \frac{1}{m}\left[-c\dot{x}(t) - k_{eq}x(t)\right] \tag{7}$$

Knowing the parameters of the system, the time solution can be determined using the differential equation solver or Matlab Simulink. The Simulink model is created, and the model is validated by the experimental data as in Fig. 9.

Rectilinear System Identification. The free response of each cart was recorded through the Arduino, ADXL accelerometers, and Matlab by displacing the carts and releasing them. As an alternative depending on the facilities, an external NI DAQ and NI Signal Express software can be utilized. For SDOF systems, each cart was connected to two springs; one on each side forming a parallel connection so that $k_{eq} = 2k$, where k is the stiffness of one spring. The loads are added on the first cart so that the masses are $m_1 = 0.317$ kg and $m_2 = 0.167\ kg$. As seen from the free response of each SDOF system shown in Fig. 10, the natural frequencies of each cart-spring system are 6 Hz and 8 Hz. Knowing the masses and natural frequencies, the equivalent stiffness, $k_{eq} = m(2\pi f_n)^2$, yields 436 N/m so that the stiffness

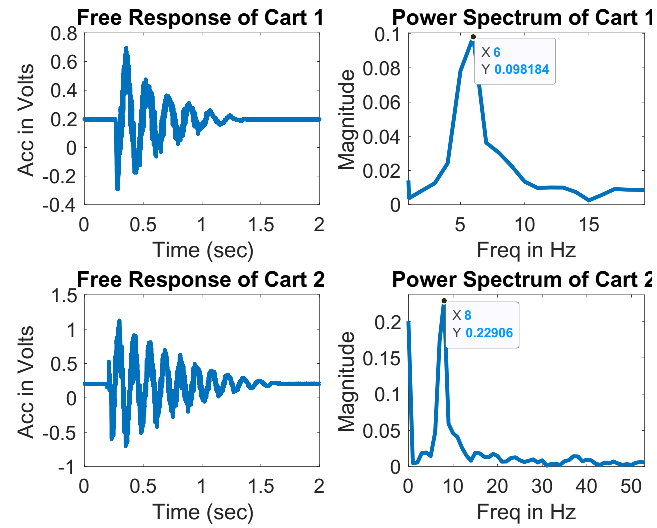

FIGURE 10: Free response and power spectrum of each cart-spring system

of each spring is 218 N/m. Since the equation of motion of each unforced SDOF system is

$$\ddot{x}(t) + \frac{c}{m}\dot{x}(t) + \frac{k}{m}x(t) = \ddot{x}(t) + 2\zeta\omega_n\dot{x}(t) + \omega_n^2 x(t) = 0 \tag{8}$$

Similar to the cantilever beam system identification, the damping constants (c_1, c_2) are calculated as 0.23 Ns/m and 0.023 Ns/m respectively. Once the carts are connected to create 2 DOF system, free response data is acquired by displacing the first cart to obtain the natural frequencies.

Rectilinear system using scotch yoke mechanism provides great advantage on the velocity and displacement control of the sliding carts. A simple PWM based output from Arduino hardware can drive the DC motor for accurate output speed as well as providing high torque. Using the same accelerometers mounted on the cart, the instantaneous acceleration can be acquired in real time as a feedback signal which then will be used to calculate the displacement without the need of additional displacement sensor. A Matlab Simulink program can control both the velocity and displacement of the carts for different desired input functions. With the simple design, this rectilinear system can be used as a low cost laboratory setup for control lab courses.

Pendulum System Identification. The rod is rotated at a certain angle and then released while reading angular position from the encoder using Arduino and Matlab code as shown in Fig 11. The length of the rod is 16.5 cm, and the tip load is 16 g. The linearized equation of motion of SDOF pendulum is

$$J\ddot{\theta}(t) + c\dot{\theta}(t) + k\theta(t) = 0 \tag{9}$$

where J is the inertia $(J = m_{tip}l_{rod}^2)$, $\ddot{\theta}, \dot{\theta}, \theta$ are the angular acceleration, angular velocity, and angular position of the rod. In this example, the power spectrum is not provided so students can

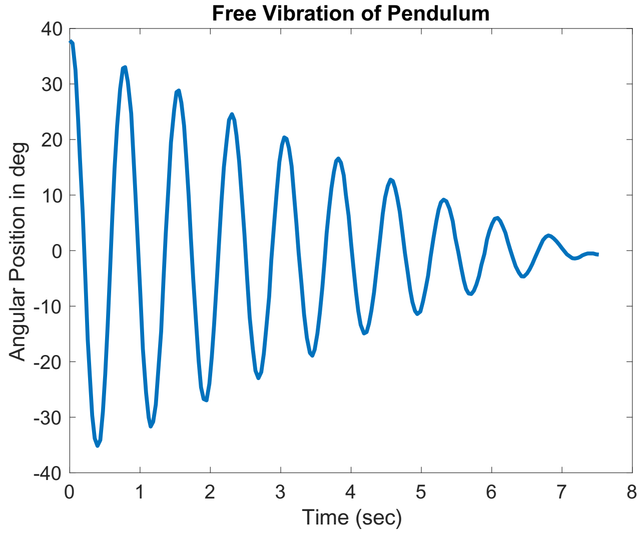

FIGURE 11: Free response data acquired from the pendulum

still find the natural frequency from the free-response data. Using the experimental data and Eqn 5, stiffness and damping can be calculated.

4. FUTURE PLANS TO STUDY STUDENT LEARNING

Future work will measure the impact of these designs on student learning. Process Oriented Guided Inquiry Learning, or POGIL [13], activities will be designed to guide students through the learning process as they use each device to connect theory to hands-on experience. At the end of the term, experimental and control groups who have and have not used the devices will be provided a worksheet with analytic and descriptive problems addressing the theoretical concepts the devices illustrate. Performance will be analyzed to determine any differences among the groups. We will also use a version of the well-known Student Assessment of Learning Gains survey [14], adapted to the intended outcomes for each device, to gather student feedback about the perceptions on the impact of the class and lab activities using the devices. Finally, we will conduct pre-post surveys using reliable and validated instruments addressing student motivation for engineering [15], engineering identity [16], and growth mindset [17] to investigate the impact of this approach to learning on those areas.

5. CONCLUSION

Since hands-on learning has a significant impact on improving student learning, there is still a demand in the design of portable laboratory equipment for mechanical engineering courses and laboratories. In this study, we present the design and development of low-cost, 3D-printed vibratory mechanisms including the pendulum, cantilever beam with springs, and rectilinear system. Although instructors can design several lab or in-class activities, case studies for the identification of system parameters are discussed.

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