Engineering Educators Bringing the World Together
2025 ASEE Annual Conference & Exposition
Palais des congrès de Montréal, Montréal, QC • June 22–25, 2025
Paper ID #46243

Multiple Representations of Learning in Vibrations and Controls: Design and Implementation of Learning Packages for Free and Controlled Pendulums

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Abstract

The challenge of learning abstract, theoretical concepts and connecting them to real-world behavior is enduring in engineering and often arises in the context of dynamics, vibrations, and control theory concepts. While hands-on experiences allow students to connect the theory and its application, most mechanical engineering courses including vibrations and control theory are 3-credit lecture-only courses without integrated laboratories. Therefore, mechanical engineering students are only exposed to hands-on learning through laboratories offered separately in the following semester or year. This time gap inhibits students' abilities to integrate theoretical concepts with hands-on experiences. This paper presents the design, development, and implementation of a hands-on free and forced pendulum device to improve student understanding of the fundamentals of modeling mechanical systems and vibrations. The equipment is portable and 3D printed at a tabletop 3D printer to reduce cost. The free pendulum portion of the kit was implemented in two sections of control theory courses. Students reported moderate learning gains and indicated the learning experience with the materials and equipment was enjoyable, while the biggest challenges were with coding and the use of Arduino to operationalize the collection of data.

1. Introduction

The learning context for this work is centered around the challenge of helping students bridge theory with practice. We have reported on this issue in multiple prior papers [1-9] but have chosen to summarize the issues here so that we can fully address the context of this work for the reader within this paper.

The challenge of learning abstract, theoretical concepts and connecting them to real-world behavior is well documented in the context of dynamics, vibrations, and control theory concepts [10-13]. The highly mathematical nature of these subjects including differential equations, Laplace transforms, linear algebra, and utilizing underlying principles to model single degree of freedom (SDOF) and multi-degrees of freedom (MDOF) mechanical /electrical /electromechanical systems pose challenges for students who may not have a strong foundation in mathematics or lack of prior knowledge in these areas. Also, students struggle with visualizing and interpreting the fundamentals of vibrations such as oscillatory motion, resonance, and damping effects in complex mechanical systems as well as grasping the fundamentals of control such as controllability, stability, root locus, and Bode diagrams [14-17].

Hands-on experiences are especially crucial for engineering students to help them bridge the gap between theory and its application [18,19]. Hands-on equipment utilized in vibrations and control labs allows students to engage with physical systems, validate theoretical concepts, identify components of a system, perform system identification, observe the output motion, and design and implement control systems. It also helps them develop practical skills and better understand concepts. However, most mechanical engineering courses including vibrations and control theory are 3-credit lecture-only courses without integrated laboratories, unlike in many electrical, computer, and mechatronics programs [20]. Therefore, mechanical engineering students are only exposed to hands-on learning through laboratories offered separately either in the following semester or year. This time gap inhibits students' abilities to integrate introduced concepts with hands-on experiences and results in reduced retention of knowledge. Lab instructors spend significant time reviewing topics from pre-requisite courses during lab, thereby reducing the time allocated for students to complete experiments. Additionally, commercially available equipment, though effective, is expensive, bulky, and comes with embedded software preventing the opportunity for students to discern signal flow and data collection with the data acquisition system. Students are limited to simply clicking "record" in the software to acquire and analyze the data. Thus, student learning through concrete, hands-on experience with the equipment is restricted to basic manipulation or even pure observation. In short, turnkey systems tend to provide little opportunity for mastery and are generally designed to minimize challenge or frustration. Also, since the equipment is heavy, instructors can't bring the equipment to the classrooms while teaching. Further, one may question issues of accessibility and equity for students. The inability to work at their own pace, repeat experiments later, and develop adequate knowledge and experience from troubleshooting the equipment and resolving problems is lacking with these turnkey solutions.

Efforts to create small, cost-effective laboratory equipment for modeling vibratory mechanical systems have had moderate success. For example, McPheron et al. developed a 2 DOF mass-spring mechanism for system identification, but the total cost including the mechanism and data acquisition system was around $1,050 [21]. Another system offered real-time control of single and multi-degree-of-freedom mass spring damper systems, but its manufacturing efficiency was not optimized [22]. Castro-Palacio et al. designed an experiment using a smartphone's free acceleration application to record oscillations of a mass-spring system [23,24]. Advancements have also been made in other areas. Molina-Bolivar and Abella-Palacios [25] created a cost-effective setup to study magnet geometry, while Kuhn and Vogt used smartphones as accelerometers in free fall experiments [26]. Ferri et al. designed a tabletop mechanism to study free vibrations and developed a mobile experiment for a control theory course [27]. To reduce costs, a smartphone attachment was used to record glider acceleration, and video recording was employed for data acquisition [28]. An experiment capturing rolling contact was designed using Tracker software [29]. MIT Precision Motion Control developed the FlexLab magnetic suspension system integrating actuators, sensors, and power amplifiers on a single board. However, despite these advancements, the equipment remains expensive [30].

2. Methods

Using the engineering research, design, and implementation process, we have developed seven vibrations and one control 3D-Printed Lab Equipment (**3D-PLE**) along with their learning activity designs with an aim to enhance student learning of the fundamentals of mechanical vibrations and control theory [1-9]. Each hands-on kit costs less than $100, including the manufacturing and data acquisition cost. Please see Figure 1 for some of our previously designed

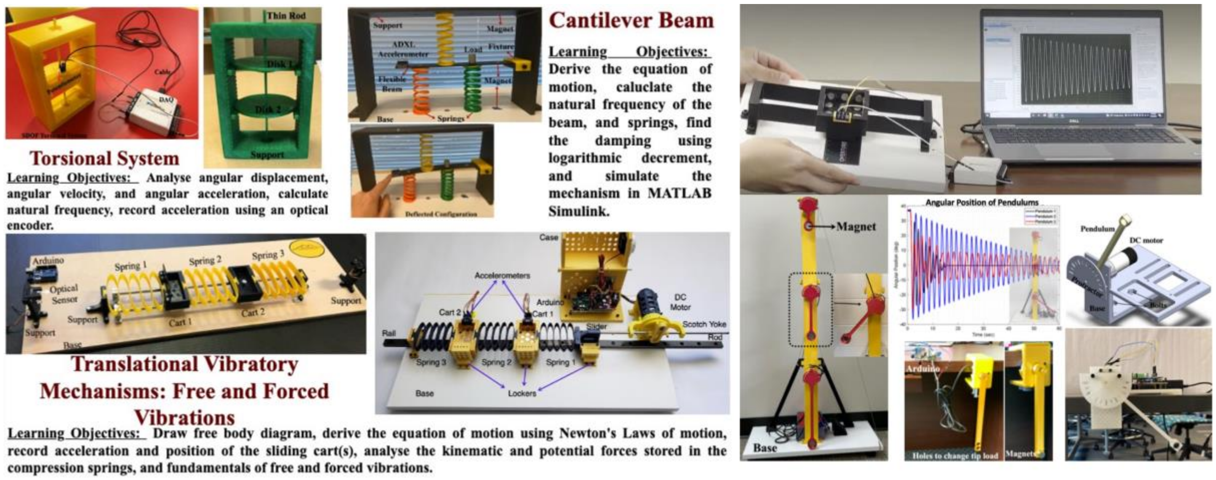


Figure 1. Examples of 3D-PLE developed for mechanical vibrations, dynamics and control courses and their laboratories

hands-on kits. This ongoing research seeks to further enhance the undergraduate curriculum that can be used for modeling, validation, and control purposes in the vibrations, control theory, and their associated laboratories that are offered in mechanical, mechatronics, and electrical and computer engineering programs. The developed equipment is portable, can be manufactured at a tabletop 3D printer using common filaments such as PLA, PETG, and TPU, and has low-cost data acquisition systems. The cad models, parts list, learning activity designed are shared openly in the project GitHub website [31]. We have employed this same research, design, and implementation process here to create a new design for a free and forced pendulum system.

Student perceptions of learning were collected from each individual student using the Student Assessment of Learning Gains (SALG) survey instrument for an assignment using the free pendulum. The survey instrument was integrated into the learning activity and a response was required in order to receive full credit on the assignment. Student responses were monitored, and later analyzed, by a co-author who did not teach the course. An IRB-approved consent form was included in the survey where students were able to choose whether their data could be used as part of the research process. Individual results from the survey were not shared with the instructor until after grades were submitted for the course. However, the co-author shared which students had completed the survey and provided a broad summary of results to help them understand how best to support continued student learning related to the assignment.

3. Design, Development, and Implementation of the Pendulum Learning Intervention

Mechanical vibrations is a 3-credit course offered in the undergraduate mechanical engineering curriculum. The course content includes the fundamentals of free and forced vibrations of single degree of freedom (SDOF) and multi-degrees of freedom (MDOF) translational and rotational systems. Vibration and control is a highly interdisciplinary field of engineering that plays a critical role in the design and analysis of complex systems. For undergraduate students aiming to

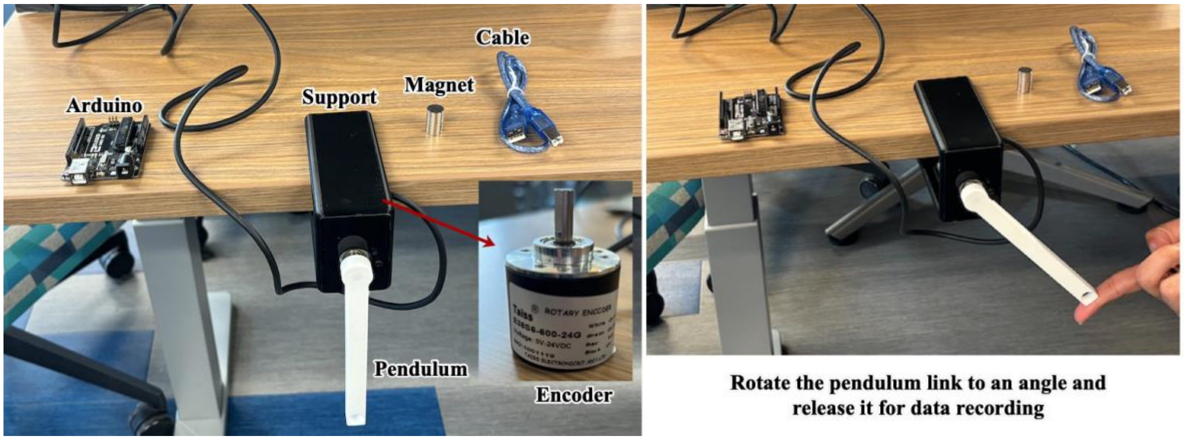


Figure 2. Previous SDOF pendulum kit including the 3D printed parts, encoder, Arduino, and magnet

make meaningful contributions soon after graduation, it is essential to deepen students' practical understanding. Developing an intuitive grasp of vibration and control parameters is crucial before attempting to design systems that require precise control. However, students often face challenges in bridging theoretical concepts with hands-on experimentation. While some excel as abstract learners, effectively applying theoretical knowledge in laboratory settings, many struggle to form these connections. This gap undermines the effectiveness of both lectures and lab activities, limiting the depth of students' learning experiences. To address this issue, a holistic approach integrating lecture content with hands-on laboratory work is needed—one that actively supports students in connecting physical experiments with foundational theoretical principles.

3.1 SDOF Free Pendulum

Design and development. We designed a low-cost and portable pendulum kit consisting of a Taiss encoder ($19), Arduino ($20), and a small magnet serving as a tip load as shown in Figure 2. Despite its simplicity, this design provides students with a tangible way to understand fundamental concepts by comparing experimental, theoretical, and simulated responses while observing physical motion.

Understanding the natural frequency of a single-degree-of-freedom (SDOF) system is foundational for engineers. Although such systems rarely exist in isolation in real-world applications, they serve as critical building blocks for analyzing more complex models. By using idealized numerical examples, instructors can introduce key concepts such as resonance, anti-resonance frequencies, principal modes, and natural frequencies. A system with two degrees of freedom, for instance, can effectively demonstrate these principles and provide insight into Rayleigh's method or the challenges of closely spaced natural frequencies. However, moving from theoretical understanding to practical application often proves difficult for students, particularly when exploring the forced and damped motions of multi-degree-of-freedom systems. While dissipation effects—such as limiting resonant motion or minimally shifting resonance frequencies—can be explained qualitatively, grasping their practical implications remains challenging. This is where SDOF systems are invaluable: near any natural frequency, the principal mode of an undamped multi-degree-of-freedom system is predominantly stimulated, making SDOF systems an ideal starting point for foundational education. To bridge the gap between theoretical knowledge and real-world application, hands-on interaction with physical systems is essential. The pendulum kit allows students to observe and manipulate parameters like damping, reinforcing their comprehension of key concepts such as principal modes and natural frequencies. By integrating experimental exploration with theoretical instruction, students not only learn more effectively but also gain a deeper appreciation for the relevance of these principles, building a stronger connection between theory and practice.

Implementation. The pendulum was utilized in two sections of the Dynamic System and Control Theory course (ME 3501), taught by one of the authors. Section 1 has 40 students enrolled, and Section 2 has 36 students. We developed 20 lab kits by 3D printing key components such as the supports and the pendulum, treated as a rigid bar. Each kit also includes an Arduino, cables, and magnets to serve as tip loads. The design of the learning activities is detailed in Appendix A, and data is collected following the completion of these activities.

Results. The SALG survey produced 76 responses to the quantitative items, and 56 comments. These were cleaned to remove duplicates and sorted by section.

<u>Quantitative survey items</u>: Analysis of the quantitative data from the SALG survey showed moderate learning gains from the assignment. While trends across the items in the survey are consistent across both sections, the students in section 1 consistently rated the statements higher than students in section 2.

Students in both sections felt they benefitted from the interaction with the professor and their peers. Results show that the quality of contact with the instructor and working with peers on the assignment received the highest average ratings from the students. The next strongest set of results related to gains in problem-solving ability. Students reported that the learning activity produced moderate gains in their ability to break down, analyze, and solve problems. Notably, students reported that their overall conceptual understanding advanced more through this learning activity than their confidence with explaining or experimentally applying that theory. These results are shown in Figure 3.

<u>Qualitative comments</u>: Upon analyzing the qualitative student comments that were left at the end of the SALG survey, several themes emerged. Each of these is described in detail below.

Affective response. Eighteen students reported generally positive emotions regarding their completion of the pendulum learning activity. Examples of generally positive emotions include students mentioning that the activity was “interesting”, “fun”, “great”, “enjoyable”, “challenging but in a good way”, “helpful”, “rewarding”, and that they “appreciated the depth.” On the other hand, thirteen students described generally negative perceptions. Examples of negative perceptions include students mentioning that they "did not like" certain elements, that the activity was "hard", "difficult", "annoying", "required a lot of work", and that they needed more support to successfully complete the activity.

Value for Learning. Useful hands-on experience with the pendulum was mentioned by six students. Moreover, four students self-reported increased learning with MATLAB and Arduino as a result of completing this activity. Five students noted that some helpful elements of the learning

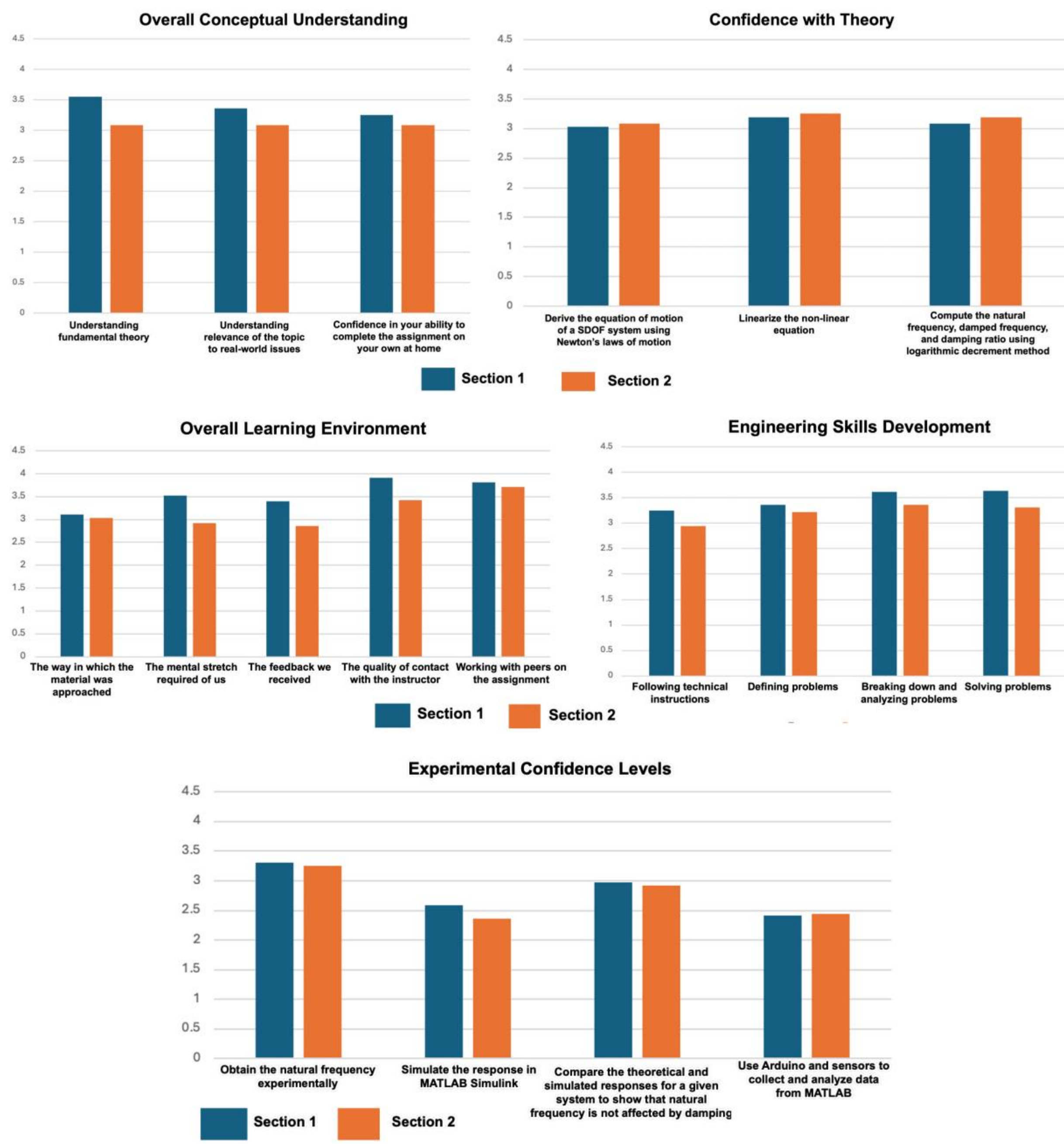


Figure 3. Results from SALG survey conducted in two sections of Dynamic Systems and Control Theory course

activity were the resources and support provided by the professor. Three students made a connection to the "why" statement from the learning activity when they noticed their understanding of theoretical concepts was reinforced and deepened through realistic simulations. One student clarified, "Using the encoder and Arduino helped reinforce my understanding of damping and natural frequency in real-world systems."

Challenges. Thirteen students reported struggles with coding and nine students recounted difficulties with using Arduino. Seven students commented that they ran into some obstacles when setting up and using the device. Two of the seven students noted troubles with the wiring and two other students in this group mentioned that the clamp was flimsy. One of these 7 students reported that there was a bolt at the pendulum connection point that blocked movement. Additionally, three students noted difficulties with scheduling group sessions outside of class to complete the learning activity. Finally, one student specifically stated that groupwork was not helpful and should not be a component of future activities.

3.2 Advanced Free and Forced Pendulum

Design and development. Since the initial pendulum design was limited to studying free and SDOF vibrations, we designed a more advanced setup to study and analyze free and forced vibrations of an oscillatory system with two pendulum rods that can. The CAD model and its prototype are shown in Fig. 4. The design incorporates a housing to support a DC motor, 3 Taiss rotary encoders, electronics such as Arduino Mega, pendulum rods, translational compliant springs, and options to change the tip loads. The end of the pendulum rods has a circular shape with a cap to enable load attachment and hold them together during motion. Both ends of the compliant springs hold magnets to easily connect them to the rods. Several compliant springs of different lengths and thicknesses were designed and developed to explore the effects of changing the spring constant. The body parts of the pendulum are 3D printed in PLA using a tabletop 3D printer. The complete mechanism weighs 845 grams, with each pendulum rod at 20 grams and additional loads of 50 grams each. The apparatus measures 30 cm in height, 24 cm in length, and 12.5 cm in width. The equipment costs approximately $100, including manufacturing costs under $5 and the data acquisition system: Arduino Mega at $23, Taiss rotary encoder at $18 each, DC motor for $15, and jumper wires for $3.

Planned implementation. The proposed equipment can be utilized in mechanical vibrations, machine dynamics courses, and vibrations and control theory laboratories. As a low-cost solution, multiple setups can be assembled to conduct experiments for both free and forced vibration analyses. These can be integrated into laboratory activities so teams of students can

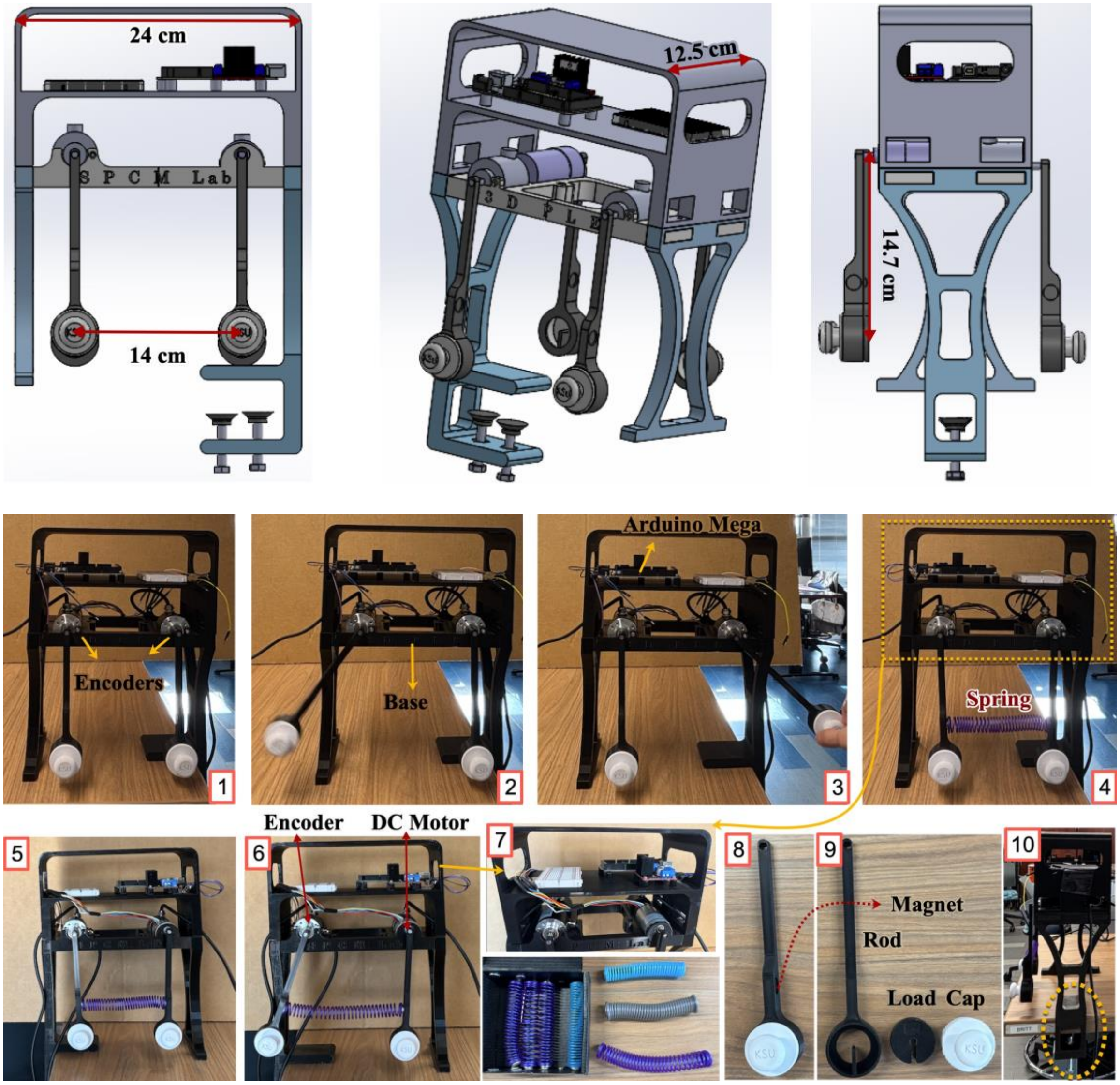
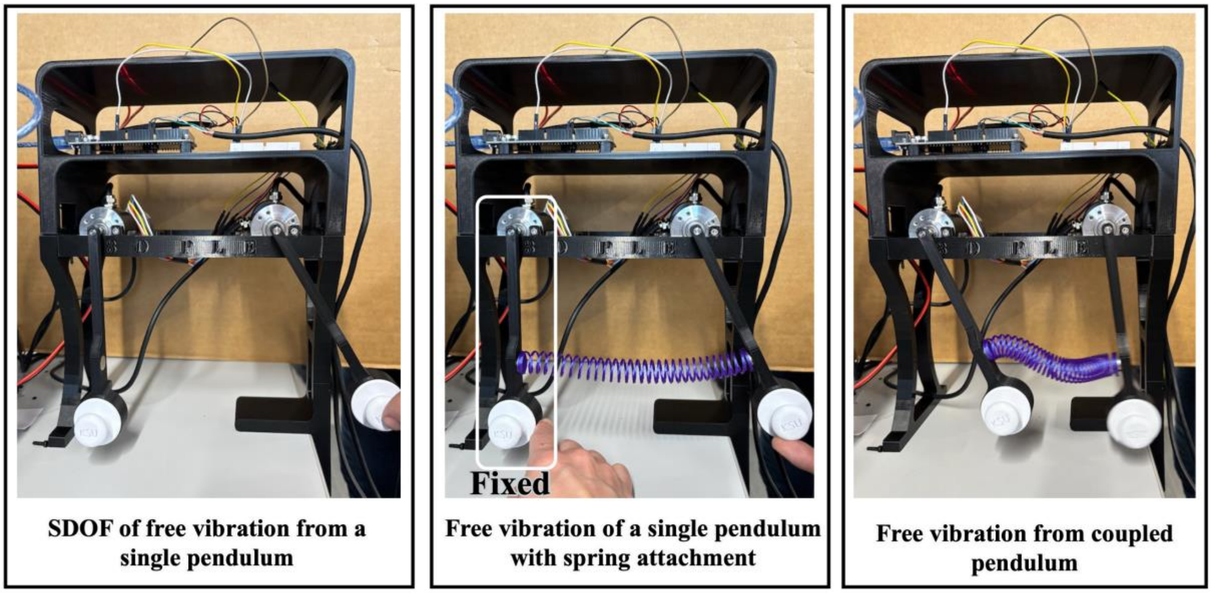


Figure 4. The top row displays the CAD models of the device from front, isometric, and left views, while the bottom row shows the physical prototype: (1-4) feature the front view with dual pendulum rods and encoders, both free and coupled together by a compliant spring; (5,6) present the back view with a DC motor on the right and an encoder on the left; (7) highlights the electronics alongside springs of varying stiffness; (8,9) examine the rod's components; and (10) depicts the setup's attachment to the table.

work on the equipment during the lab, or as homework assignments, or group projects in traditionally taught face-to-face courses. While mechanical engineering students excel in design and problem-solving, they often have limited exposure to programming. Therefore, this type of hands-on equipment is crucial and provides them with essential wiring and programming experience.



(a) (b) (c)

Figure 5. Implementation of our 3D-printed pendulum setup for (a) a simple pendulum, (b) a pendulum with a spring, and (c) 2 DOF coupled pendulum

Learning objectives and theory addressed. The learning objectives that can be achieved with our proposed 3D-printed pendulum setup include: (1) assembling the equipment, (2) collecting angular position data from rotary encoders during free movement, (3) actuating the DC motor and capturing angular position data from embedded systems or rotary encoders, (4) deriving equations of motion for single-degree-of-freedom (SDOF) and two-degree-of-freedom (2DOF) systems, (5) calculating the moment of inertia of the pendulum, (6) performing system identification to determine unknown parameters such as equivalent stiffness and damping constants using the logarithmic decrement method, (7) simulating the mathematical model in MATLAB Simulink, and (8) comparing theoretical and simulated models with experimental data.

The following case study showcases the implementation of the proposed learning objectives through the analysis of three distinct mechanical systems: a single-degree-of-freedom (SDOF) pendulum, a single pendulum with a spring, and a 2DOF system with coupled springs as the images of each setup are shown in Fig. 5.

The mathematical model of an unforced single pendulum using Newton's laws of motion is described by a second-order homogenous differential equation

$$I\ddot{\theta}(t) + B\dot{\theta}(t) + K\theta(t) = 0 \qquad (1)$$

where $I, \theta, \dot{\theta}(t), \ddot{\theta}, B, K$, and t are the moment of inertia, angular position, angular velocity, angular acceleration, damping constant, stiffness, and time correspondingly. The moment of inertia of the pendulum with a non-negligible mass and a radius of the tip load is

$$I = \frac{1}{12} m_r L^2 + m_r \left(\frac{L}{2}\right)^2 + \frac{1}{2} m_t r^2 + m(r+L) \qquad (2)$$

Here m_r, m_t, m are the masses of the rod, tip, and extra load, L and r are the length of the rod and radius of the circular tip. Since the mass of the rod and the tip are 5 grams and 15 grams, the length of the rod is 12.7 cm, and the radius of the circular tip is 2 cm, the moment of inertia is calculated as 0.0074 kgm^2. The unknown parameters of an underdamped mechanical system can be obtained using the logarithmic decrement method.

From the experimental setup (a) and the free vibration data acquired from the encoder simply by rotating the pendulum to 37°, and releasing from rest, and logarithmic decrement (δ), damping ratio (ζ), damped period (T_d), damped frequency (f_d), damped angular frequency (ω_d), and angular frequency (ω_n) can be calculated as illustrated in Fig. 5. By simplifying Eqn. 1 and making an analogy with its damping ratio and natural frequency form, the damping constant (*B*) and stiffness (*K*) are found to be 0.0014 Nms/rad and 0.062 Nm/rad.

Determining the stiffness of a compliant spring is difficult, especially at the undergraduate level. However, the stiffness can be calculated using experimental data. The period of oscillations of a pendulum with a bob mass (m_t+m_r) attached to a horizontal spring fixed at one end, similar to Fig. 5b, is $T = 2\pi\sqrt{\frac{mL^2}{Kh^2+mgL}}$ where *k* represents the stiffness of the spring, *g* is the gravitational acceleration, and *h* is the distance from the fixed point of the pendulum to the spring connection, which is 10.3 cm. Reading elapsed time between two consecutive data acquired from the setup shown in Fig 5b, the stiffness of the compliant spring yields 18 N/m. Assuming the spring is connected to the same length as the rod and knowing the stiffness of the compliant spring, two coupled identical springs, as illustrated in Fig. 5c can be studied to further derive the mathematical model of 2 DOF and analyze coupled springs, mode ratios, and eigenvalues. For instance, the natural frequencies of a coupled spring are $\omega_1 = \sqrt{\frac{g}{L}}$, and $\omega_2 = \sqrt{\frac{g}{L} + \frac{2k}{m_{total}}}$.

Finally, MATLAB Simulink model can be created to solve Equation 1 using the calculated values to compare the simulated model with experimental data.

In addition to these examples, instructors can use the same equipment to design different learning activities or in-class short demonstrations that enhance students' understanding of both basic and advanced concepts in modeling and vibrations.

4. Conclusion and Future Work

The integration of hands-on equipment into mechanical engineering courses not only enhances students' learning experiences but also provides opportunities to develop practical skills such as reading experimental data through a low-cost data acquisition system and wiring electronics and coding. This study presents the implementation of a previously designed single-degree-of-freedom (SDOF) pendulum in the Dynamic Systems and Control Theory course, offered to junior and senior mechanical engineering students. Furthermore, this paper introduces the design and development of an advanced and more compact pendulum setup to be utilized in the mechanical vibrations and control theory courses and their laboratories. The setup demonstrates the free and forced responses of both SDOF and multi-degree-of-freedom (MDOF) rotational systems. The portable equipment includes four pendulum rods (two on each side), translational springs, three Taiss encoders, a DC motor, and an Arduino Mega for angular displacement data recording and actuation. All components are 3D-printed using PLA filament, with the total cost of the hands-on kit approximately $100. Users can design an SDOF pendulum to collect free response data for system identification, connect a spring between two rods to calculate the stiffness of the 3D-printed spring using free response data and create a 2-DOF system to study coupled pendulums. Additionally, users can perform forced pendulum experiments through DC motor actuation. Instructors can utilize the kit to provide in-class demonstrations while teaching the fundamentals of mechanical system modeling or vibrations. Alternatively, the hands-on kit can serve as a lab activity in vibrations and control laboratories or as a team-based homework assignment in vibrations and control theory courses.

As a future consideration, the advanced pendulum setup will be implemented more extensively across listed courses by 3D printing multiple identical kits. This scalability would allow students to individually or collaboratively work with the equipment in laboratory settings and promote engagement with hands-on experiments. Additionally, we will explore its impact on students' understanding of dynamic systems of advanced topics such as system coupling and forced vibration analysis.

Acknowledgement:

The authors gratefully acknowledge the support of the National Science Foundation award number 2336998. The authors sincerely thank all the students who worked on the project and Prof. Richard Kennedy, director of the Southern Polytechnic College of Engineering and Engineering Technology 3D Printing Lab, for his support.

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Appendix A – Pendulum Homework

Course	**Dynamic Systems and Control Theory**
Activity Title	Pendulum motion – exploring oscillation frequency
Why	Natural frequency is a critical design parameter which we must know in order to avoid having a system fail (by violently breaking apart, for example) if it vibrates near its natural frequency. Natural frequency is a function of stiffness and mass, which can be determined relatively easily for any system.
Time recommended to complete this homework assignment	You have two weeks to complete this assignment.
Learning objective(s)	1. Derive the equation of motion of a SDOF using Newton's laws of motion. 2. Linearize the nonlinear equation of motion. 3. Compute the natural frequency, damped frequency and damping ratio of the system using logarithmic decrement method. 4. Obtain the natural frequency both experimentally and theoretically. 5. Simulate the response of the system in MATLAB Simulink. 6. Compare theoretical and simulated responses for a given system to show that natural frequency is not affected by damping.
Performance criteria (behaviors you should follow to perform the activity well)	Confirm prerequisite knowledge needed for activity has been addressed by reviewing course notes and textbook: • Natural frequency • Modeling a pendulum Use differential calculus solutions to complete your analysis of this system. Validate the measured data and modify data set appropriately for further analysis. Report outcomes using professional language that reflects deep thinking for interpretation of results. Use appropriate resources such as Copilot (recommended) to generate necessary codes and websites for wiring the encoder and Arduino.
Connections (to other topics, content areas, real-world applications)	This lab integrates the fundamentals of vibrations from ENGR 3125 (Machine Dynamics and Vibrations) such as natural frequency, free response of SDOF systems, data measurement from smartphone embedded accelerometer, and system analysis using MATLAB Simulink.

Instructions - after reviewing this entire activity, do these in order

1. Review the general theoretical model for SDOF systems - Refer to your Machine Dynamics and Vibrations Chapter 1 and Chapter 2 in-class notes that are shared in D2L.
2. Answer the **preliminary questions** on the next page of this handout (graded only for completion). It should be completed by each student separately and uploaded as a separate pdf.
3. Study the experimental system we are analyzing for this homework by downloading the ppt from D2L in the Homework folder and viewing the embedded video.
4. Gather the resources needed to complete the analysis
    a. Download MATLAB R2024a by selecting the all toolboxes.
    b. Download Arduino Support Package or follow the instructions provided in D2L with the title of Instructions for Downloading Arduino Support Package for MATLAB.
5. Answer the **procedures and calculation questions** (sections A-E below) on this handout. Please show **all** your work to receive full credit.

    Also please include all questions (at least one) you have asked in the copilot for any part of the procedures. We are currently developing AI tools to implement in the virtual lab simulations and the learning activity designs. Therefore, we need this information to help us design the most effective AI assistance.

6. Upload your homework (your responses to the preliminary questions and sections A-E below) in pdf form in D2L before the deadline.
7. Complete the survey for this homework using the link provided by your instructor.

Preliminary Questions (graded on completion only, take no more than 30 seconds and write worn what comes to your head, and if you don't recall, then write down anything related)

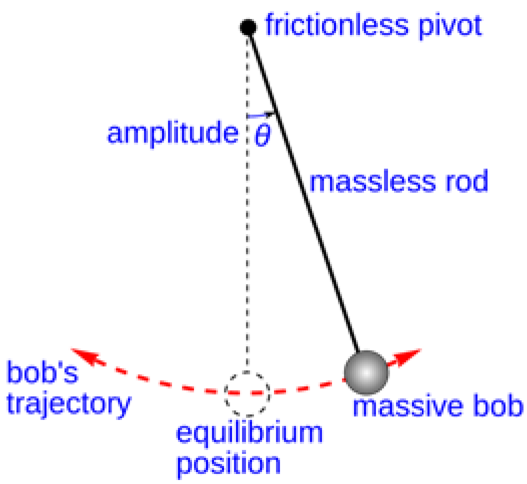
1. What is the difference between undamped natural frequency and damped natural frequency?

2. How would you collect experimental data from the pendulum when it's given an initial angular, θ_0. In other words, what physical variables will you be measuring, and what are the corresponding sensor(s) that can be used to record those measurements?

3. How do you calculate the natural frequency of a system using experimental data?

4. List possible ways/methods to find the damping coefficient/constant of a system.

A. Theoretical Modeling using Newton’s Laws of Motion



Free Response of the Pendulum:

The length of the rod is L and mass of the tip load is m. Each magnet is 2 grams.

The pendulum is initially rotated by θ_0°.

Dimensions:

Length of the rod:	
Mass of the tip load:	
Initial angular position:	

Refer to Free Vibration of SDOF Systems COMPLETED notes shared in D2L. Pages 24-29 briefly present the solution of SDOF translational systems consisting of a spring and a damper element. Since your system is rotational, rewrite the equations by replacing

$x(t), \dot{x}(t), \ddot{x}(t)$ with $\theta(t), \dot{\theta}(t), \ddot{\theta}(t)$ in the same order.

1. Derive the equation of motion of the pendulum given in the below sketch. Show all your work including the free-body diagram and the equations.

   Write the equations below.

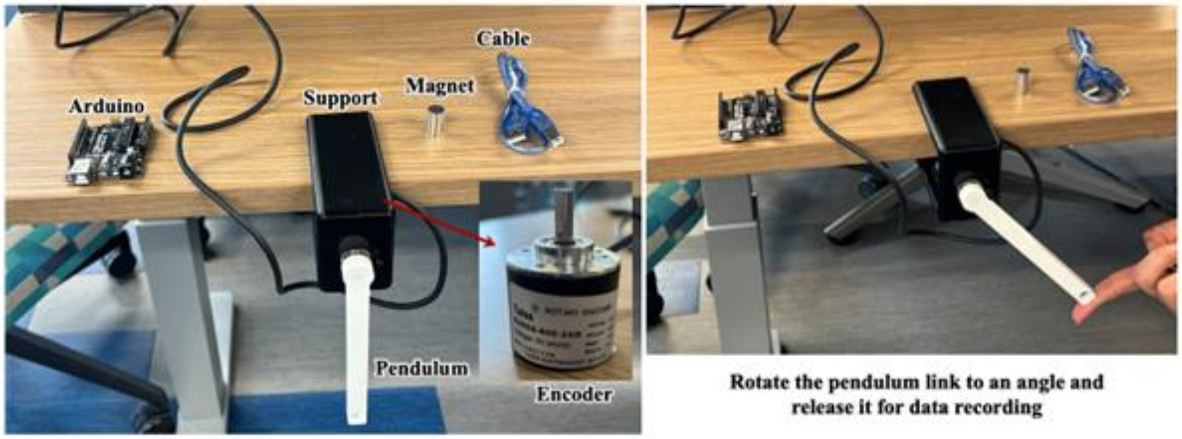
2. Linearize the equation of motion of the pendulum for small angular displacements.

   Write the linearized equation below.

3. Write the solution of the differential equation referring to the notes for the free response of SDOF systems. Use variables since the numeric values are not known yet.

   Write the solution below.

B. Experimental Data Collection and Calculations



3D-Printed Pendulum Lab Kit.

To learn this material, it's important for everyone to get hands-on experience. Please show that you are working together to get the hands-on experience by sharing a picture of your group meeting. (Or a recorded Teams meeting)

Please show all your work to get full credit.

1. Connect the encoder (Taiss E38S6-600-24G) to Arduino. Use web resources to find the wiring diagram.
2. Mount the pendulum to a table using the bolts.
3. Write a script to connect and read data from the encoder. You are allowed to use resources such as Copilot (recommended) to generate necessary codes.
4. Run the code while the pendulum is positioned vertically downward. If you rotate the pendulum to an angle before running the code, that initial angle is set to be zero degrees in the encoder. Instead, run the code and wait for the figure window to open. Then rotate the pendulum to an initial angle (don't forget to measure the angle!) and release.
5. Record data. (You should upload the MATLAB workspace data as a mat file in D2L together with homework solution).
6. Plot the time vs angular displacement data in MATLAB. If you need help with plotting data in MATLAB, please refer to the Downloading Data notes shared in D2L or watch the Download and Plot Data in MATLAB video.

Copy and paste the MATLAB figure below.

7. Calculate the damped period, damped frequency, logarithmic decrement, damping ratio, damped frequency (in rad/sec), natural frequency (in rad/sec) and damping constant of the system. **Note:** Refer to pages 31 or 65 on Free Vibration of SDOF Systems COMPLETED notes. An example is shown on Page 67. Please make sure to modify your graph so that the oscillations are around 0 and the initial time starts from t=0 seconds.

   Show all calculations below.

C. Model Validation and Simulation

Please watch the Pendulum Lab Activity video if you need assistance in creating the MATLAB Simulink model of 2^{nd} order differential equations. This video was created for students taking ME 4501 and using the pendulum as their lab activity. Although your learning activity design is slightly different from theirs, the MATLAB Simulink model is the same as shown in the video.

1. Simulate the theoretical equation you derived in Section A.2 in MATLAB Simulink using the numeric values calculated in Section B7.

   Share the image of the Simulink model below.

2. Import the experimental data in MATLAB Simulink and compare the experimental data with the simulation output.
3. Is there any difference between the simulation response and experimental data? If yes, please comment on the possible reasons.

   Write your response below and copy and paste the MATLAB figure showing both the simulated and experimental data.

D. Analysis (post-processing) Questions

1. Rewrite the equation of motion of the pendulum assuming:
   A. The pendulum has no damping: frictionless pivot.

      Write the equation below.

   B. The pendulum has some damping: friction is not neglected. Use the damping constant you calculated in Section B.7.

Write the equation below.

C. Using the same dimensions and initial angular displacement; simulate the response of both systems (damped and undamped) in MATLAB Simulink.
D. Compare the frequency of the damped and undamped oscillations. Is there a significant difference in the frequency of oscillations?

Copy and paste the scope images or the MATLAB figures below.

E. Critical Thinking Questions

Write the answer to each question below.

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 homework (review the learning objectives to help you decide)?
3. What are three applications (in addition to a pendulum system) where you might use these concepts?
4. What is the muddiest point remaining that you haven't yet mastered?
5. Write out one question you can ask your instructor to clear this up.

Device Survey - Complete this survey about this pendulum device homework.

Complete the survey for this homework using the link provided by your instructor.