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LEARNING BY DOING IN THE DYNAMICS AND MECHANICAL VIBRATIONS COURSES USING 3D PRINTED EQUIPMENT

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ABSTRACT

Limited resources available to the engineering faculty and students impede student learning and deep understanding of the material that is presented in the dynamics and mechanical vibrations courses. Active learning practices such as learning by doing is an effective way to not only build a solid foundation in knowledge but also help students develop engineering skills. However, these courses are mainly taught in a traditional manner and many students struggle in connecting the theory to its real-world application and lose interest. Although mechanical engineering students get more hands-on opportunities in the laboratories, they take vibrations and control laboratories in the following semesters since vibrations is a pre-requisite for these labs. To address this issue, we designed 3 low-cost, compact, and portable laboratory equipment and fabricated them using 3D printing technology. The first equipment is a 3-pendulum system with different lengths and tip loads that can be utilized in the engineering dynamics course. While the second equipment is a 2 DOF compliant vibration isolator consisting of flexible beams, masses, and a linear actuator, the third equipment is a non-linear cantilever beam to be utilized in the vibrations courses and their associated laboratories.

Keywords: Engineering education; mechanical vibrations, engineering dynamics, hands-on experiences

NOMENCLATURE

Place nomenclature section, if needed, here. Nomenclature should be given in a column, like this:

M_i	mass i
k	spring constant
F	Force
E	Young's modulus
$\theta, \ddot{\theta}$	Angular position, angular acceleration
$x, \ddot{x}$	Displacement, acceleration
I	Polar moment of inertia

1. INTRODUCTION

The vast majority of undergraduate-level mechanical engineering students struggle in vibrations and control theory courses due to the highly complex nature of the theory and limited resources on the use of commercially available equipment as these factors adversely affect the graduation rates and inhibit student learning [1-6]. Keeping engineering students' engagement and interest in a class throughout the semester is challenging. Students often lose their interest when they get overwhelmed with highly mathematical concepts especially when these courses are taught in a traditional manner in which the instructor presents the topic and supports the material with class projects and homework assignments. In these classes, instructors need to provide interactive and constructive learning opportunities for students to develop a better understanding of the fundamental concepts. However, with diminishing resources available to faculty, it is difficult to teach fundamental and abstract concepts. Although prior research on active learning has shown promising results in improving student learning [6], adopting learner-centered teaching in engineering courses requires a significant effort, such that the instructor can create in-class activities encouraging student participation and utilize technology to demonstrate or visualize abstract concepts. However, considering the engineering faculties' heavy workload and research requirements, faculty might not find adequate time and resources to create activities for their courses.

Since engineering involves the use of scientific principles to solve real-world problems, it is essential that the theoretical concepts imparted to the students in a traditional classroom setting are supported by practical experience through hands-on experiments [7-11]. One salient but also the most challenging ABET outcome to achieve is that an engineering graduate should have the ability to solve a well-defined engineering problem by combining theory and practice [12]. Improving students' problem-solving skills is a requisite to educate new engineers who can meet today's challenges and become experts in their field of interest.

Integration of hands-on activities in a traditional classroom empowers student learning. For this purpose, Ferri et al. designed a 2 DOF oscillatory system comprised of a scotch yoke mechanism actuated by permanent magnets and two metallic springs with tip loads [13]. Lewis et al. designed a 3 DOF vibratory system driven by a linear actuator to demonstrate resonance and control of vibration [14]. A rectilinear mass-spring system actuated by a scotch yoke mechanism was built to study the basics of vibrations in [4] and a SDOF compliant parallel-arm system with fixed-free flexible beams and a hanging mass was built to perform system identification in [5], and Tekes developed a SDOF rotational system with a rod, disk, and additional loads to demonstrate how the change in inertia effects the natural frequency of the system [6]. Johns designed and developed a 2 DOF vibration isolator/resonator while recording positions of the masses using a laser displacement sensor [2]. Giannakakos developed a 2 DOF compliant vibratory mechanism consisting of a rail, and two carts that are connected through two rigid arm-large deflecting hinge links [5]. Compression springs were replaced by compliant hinges to reduce the cost. Jacobs et al. designed a control lab test setup for an advanced linear control theory course using a flexible beam [15].

There is still demand for the development of low-cost, portable, and single degrees of freedom (SDOF) and multi degrees of freedom (MDOF) vibratory mechanisms. To overcome the aforementioned challenges in teaching and learning traditionally taught dynamics, and vibrations courses, we designed and developed portable, compact, and 3D printed equipment so instructors can carry it to classrooms for demonstrating the abstract concept or assign them as homework. The proposed equipment are 3 pendulum system, 2 DOF compliant isolator mechanism, and a cantilever beam.

The paper is structured as follows. The design and fabrication of the devices are presented in Section 2. Learning activities that are tied to the equipment are discussed in Section 3. Concluding remarks are provided in the conclusion.

2. DESIGN AND DEVELOPMENT OF HANDS-ON EQUIPMENT

This section briefly discussed the design and development of each equipment that could be utilized in the engineering dynamics and mechanical vibrations courses.All materials and

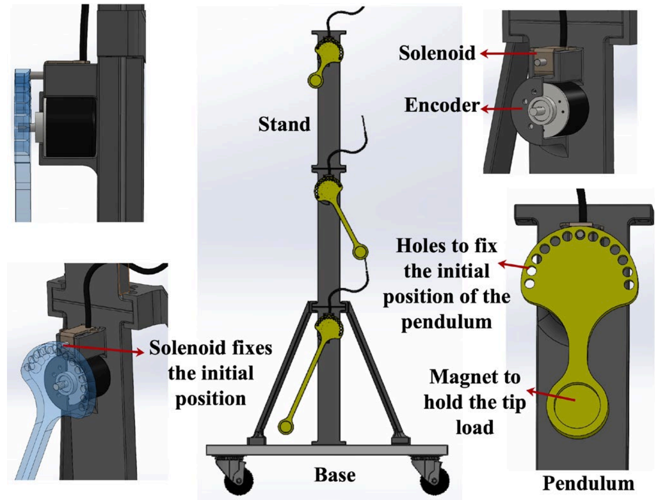


FIGURE 1: Cad model of the 3 pendulum system

methods that have been used in the work must be stated clearly. Subtitles should be used when necessary.

2.1 Pendulum System

Engineering dynamics is one of the fundamental engineering courses that mechanical engineering students take as a sophomore. The course content is focused on the kinematics and kinetics of particles and rigid body dynamics. Since engineering dynamics is the prerequisite of the mechanical vibrations course, students are expected to build a solid foundation in modeling rigid bodies using the theory they learned in dynamics.

We designed a pendulum system consisting of 3 rods, magnetic tip loads, a stand, base, three encoders, and three solenoids as the cad model is shown in Fig. 1. The pendulums have different lengths, and the tip of each pendulum is designed in a way to accommodate more magnets to change the effective mass. The other end of the pendulum has a circular shape with holes on it to rotate the pendulum at a desired initial angle and fix its position. 3 encoders and solenoid housings are placed on the back of the rod. The electronic box has three Arduinos (one to control relays to the solenoids and 2 are used to record data from the encoders). While the encoders are powered by the Arduino, solenoids are powered by the battery pack.

First, we fabricated all parts of the pendulum including the rod, pendulums, housing parts, and the electronic box by 3D printing using polylactic acid (PLA). Then all parts are assembled as seen in Fig. 2. In addition to the equipment itself, we purchased 3 Taiss rotary encoders each at a cost of \$18, two Arduinos (3x\$15), battery pack (\$20) to power the Arduino and control switches.

2.2 Flexible Beam with Springs

Students learn the fundamentals of vibrations in undergraduate level vibrations courses that start with finding the equivalent mass-spring-damper models of a vibratory system along with the free and forced response of SDOF and 2DOF

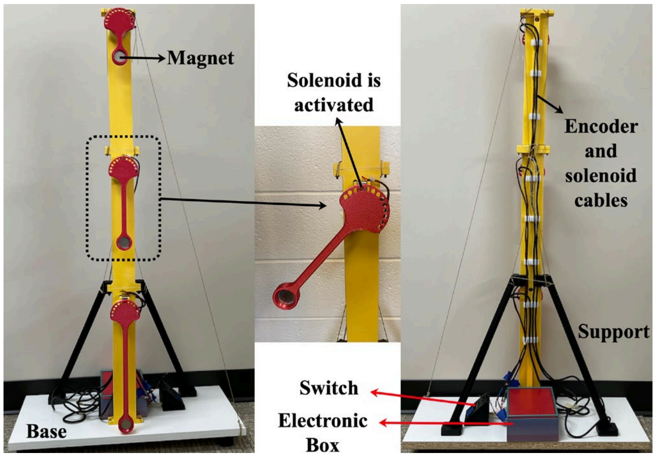


FIGURE 2: Prototype pf the 3 pendulum system

systems. Unlike electrical, mechatronics and robotics programs, mechanical engineering students are offered the laboratory course in the following semester preventing students to link the theory and its application area. We designed a fixed-free flexible beam with springs to study finding the equivalent mass-spring-damper of a vibratory system using experimental data. The fixed-free beam has magnets at fixed-distances so one can attach the compression springs at different locations. The compression springs also have magnets at both ends to couple them with the beam. Several beams and compression springs are 3D printed using PLA and polypropylene terephthalate glycol (PETG) to change their elasticity thereby deflection under the same loading as an example system is depicted in Fig. 3. Data can be recorded using low-cost data acquisition system with an ADXL accelerometer ($15) and Arduino ($15) or through uni-axial or tri-axial PCB accelerometers and NI data acquisition card (DAQ) depending on the available equipment. Additional loads can be attached to the beam either using magnets or double-sided tape. Since all parts of the cantilever beam with springs are 3D printed and we prefer low-cost data acquisition by MATLAB, the total cost of the equipment is less than $50.

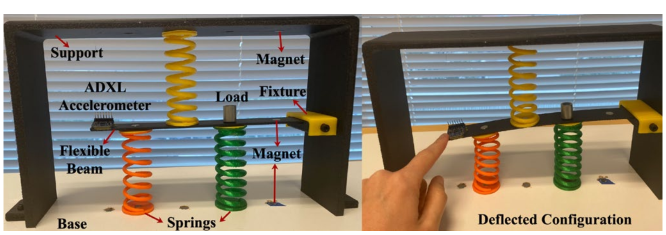


FIGURE 3: Undeflected and deflected configurations of 3D printed fixed-free flexible beam with springs

2.3 Compliant Vibration Isolator

Modeling an oscillatory system is a topic covered in the mechanical vibrations courses and their associated laboratories. Students also learn to design a vibration isolator when the mass-spring-damper system is subjected to base excitation in vibrations courses. The educational turn-key equipment is limited to either simple translational mass-spring-damper systems where the mass slides on a rail and is connected to the helical springs and rotational systems with a fixed-fixed rod and a disk. However, in practice, the stiffness of a system is not only due to the conventional springs, and anything elastic, thin and long serves as a spring. To better illustrate it, we designed a vibratory system consisting of motor housing, fixture, base, two large deflecting flexible beams and mass which is subjected to base excitation through a compliant parallel arm and a linear actuator to reduce the cost as shown in Fig 4a. The linear actuator is connected to the SDOF compliant parallel arm so that the vibratory system will be displaced only in one direction while controlling its amplitude and frequency. The system also has a vibration isolator with an additional mass and flexible beam as shown in Fig. 4b.

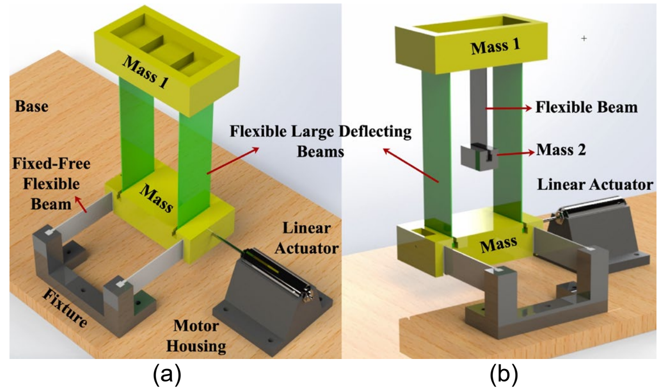


FIGURE 4: (a) Oscillatory system driven by a compliant parallel arm without the vibration isolator and (b) with the isolator

Masses, motor housing and fixtures are 3D printed using PLA and flexible beams are 3D printed in PETG and assembled together as shown in Fig. 5. Accelerometers are attached to each mass to record data using NI DAQ while controlling the force amplitude and frequency of the linear actuator.

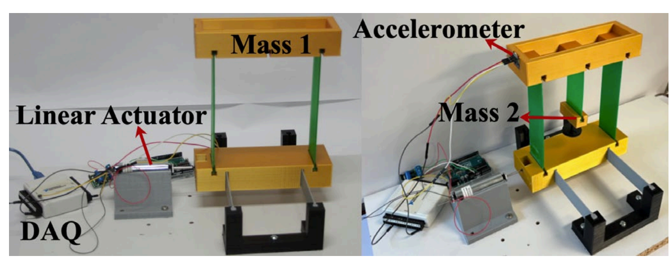


FIGURE 5: Experimental setup for the original system and with the isolator design

3. THEORY RELATED TO THE EQUIPMENT

The proposed 3D printed, and portable laboratory equipment can be utilized in engineering dynamics, introductory-level mechanical vibrations, control theory, and their associated laboratories. The instructor can use the equipment only for demonstration purposes in the class before or after teaching the topic. Additionally, since the equipment is low

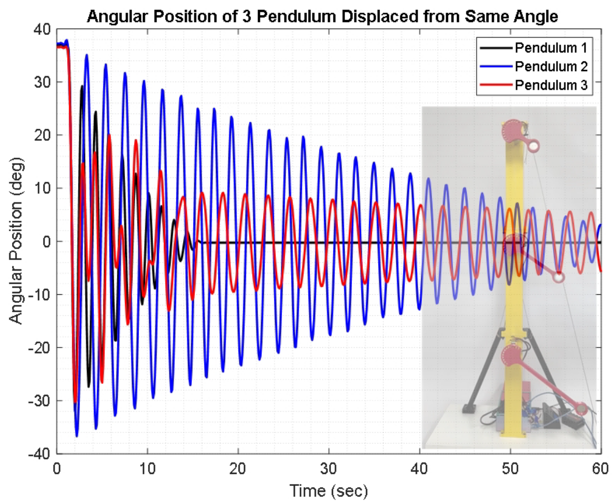


FIGURE 6: A demonstration on what affects the frequency of oscillations using 3 Pendulum system

cost and can be manufactured at a home type 3D printer, more of the same setups can be build and assigned as a group project or a team lab activity for laboratories.

3.1 Pendulum

Deriving the equation of motion of a translational and rotational mechanical system is part of the dynamics, vibrations, and control theory courses. One common example is the vibrations of the pendulum. The nonlinear equation of motion of a simple pendulum pinned at its one end is

$$\ddot{\theta}(t) + \frac{c}{ml}\dot{\theta}(t) + \frac{g}{l}sin\theta(t) = T(t) \quad (1)$$

where $\theta, \dot{\theta}, \ddot{\theta}$ are the angular position, velocity, and acceleration of the pendulum and m, c, g, l, T are the tip mass, damping constant, gravitational acceleration, length, and applied torque. Since Eqn.1 can be linearized for small angular displacements ad rewritten in terms of ζ (damping ratio) and ω_n (natural frequency) as

$$\ddot{\theta}(t) + 2\zeta\omega_n\dot{\theta}(t) + \omega_n^2\theta(t) = T(t) \quad (2)$$

Making an analogy between Eqns. 1 and 2, the natural frequency of the pendulum is $\sqrt{g/l}$, and only depends on the length of the pendulum. While the instructor can use experimental data acquired from the pendulum system to perform system identification to determine the unknowns such as damping constant and damping ratio, the 3 pendulum setup can be utilized to demonstrate what affects the pendulum's frequency of oscillations.

The 3-pendulum system allows locking the position of each pendulum at its initial angles and release by controlling the solenoids through the switch. The switch has 3 buttons to actuate the solenoids. If the pendulums are rotated to the desired angle and the switch is turned on for the specific pendulum, the rod on the solenoid will move inside the hole and keep the pendulum at that location. Once the pendulums are released through the buttons on the switch, the free oscillations can be recorded using the encoders, Arduino, and MATLAB.

The instructor can start the class with a discussion on what affects the frequency of oscillations of a pendulum such as its tip load, tip mass, initial angle, or length. To illustrate one example, we attached 3 pendulum rods having different lengths but the same tip load and displaced them all to the same angle, and released as the recorded data is shown in Fig. 6. Also, same length rods can be attached to demonstrate the effect of the initial angle by rotating them to different angles or adding more mass using the magnets while showing the angular displacement acquired from the encoders on the screen.

3.2 Cantilever Beam

Engineering students learn the free and forced response of mechanical systems such as cantilever beams in the mechanical vibrations courses. If the theory can be integrated with its application, student learning will be enhanced, and they will be able to make the transition from the theory to its practical application easily. Integrating applications while teaching fundamentals of vibrations reinforce student in a traditional classroom that keeps students' attention and interest. Learning is a continuous cycle including prior knowledge, hands-on experience, and reflection. The instructor can teach the fundamentals of free response vibrations using our 3D printed and portable cantilever beam with springs. The oscillations on the fixed-free beam can be recorded simply by displacing the cantilever beam and recording the acceleration using Arduino/NI DAQ and MATLAB. A further discussion on "Where do we see such examples?" leads to critical thinking. One good example is the wind-induced oscillations on traffic signal structures as illustrated in Fig. 7.

The stiffness (k) of a flexible cantilever beam loaded at point A is

$$k = \frac{6EI}{3Lx_A^2 - L^3} \quad (3)$$

and if loaded at its tip, then the stiffness simplifies into

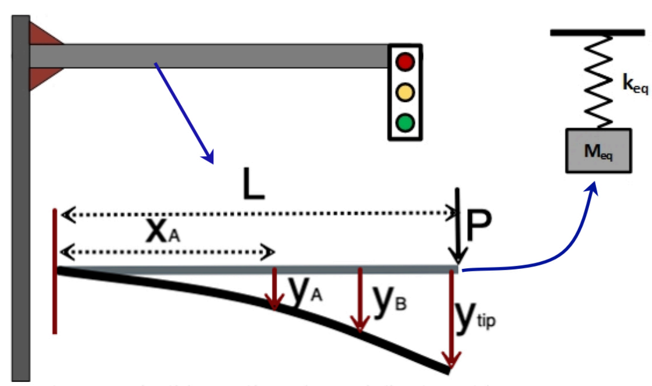


FIGURE 7: Sketch of traffic signal structure by its equivalent mass-spring model

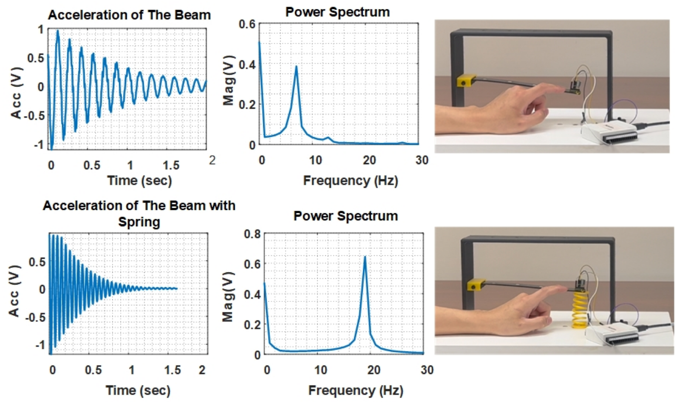


FIGURE 8: (a) Sketch of the compliant mechanism and (b) with the vibration isolator

$$k = \frac{3EI}{L^3} \tag{4}$$

where E is the Young's modulus, I is the polar moment of inertia ($=bh^3/12$), b and h are the width and thicknesses of the beam.

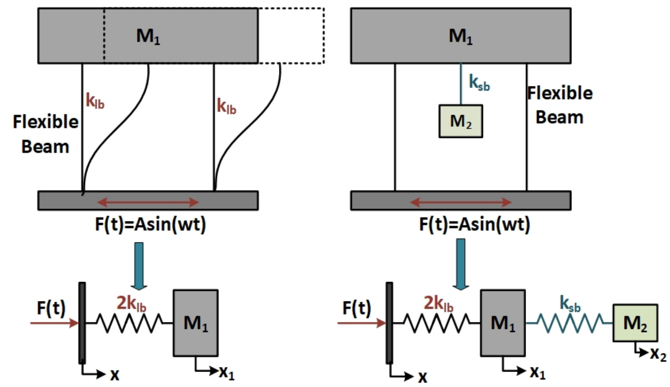
The cantilever beam can be utilized in the classroom or in the lab to improve students' theoretical modeling skills, conducting experimental testing and performing system identification. If the free response data is recorded using the ADXL accelerometer from the beam when provided an initial displacement, the natural frequency of the beam can be calculated either using the free-response data or plotting the power spectrum. Knowing the natural frequency and equivalent mass, the stiffness of the beam can be calculated. The second step is the calculation of spring constant of each 3D printed torsional springs. Students can attach one spring at a time to the tip, record data as in the previous step, plot the power spectrum and calculate the new natural frequency as shown in Fig. 8. Since the natural frequency of the beam is known, the stiffness of the compression springs can be obtained from the new equivalent stiffness. Finally, a new setup can be built by attaching multiple springs, the equations of motion can be derived using the theory and the responses can be compared with the experimental setup.

3.3 Compliant Vibration Isolator

The oscillations in a mechanical system are usually undesired and should be eliminated with the design of an active controller or passively by attaching a secondary system such as a mass and a spring. There is available laboratory equipment for the demonstration of vibration isolator design. However, they are expensive and not portable since the base motion is induced by a shaker. The presented portable compliant mechanism is subjected to base excitation via a linear actuator and the system itself consists of 3D printed masses and flexible beams as shown in Fig.9.

The equation of motion of the compliant mechanism is

$$M_1\ddot{x}_1(t) + 2k_{lb}x_1(t) = F(t) = Asin(\omega t) \tag{5}$$



(a) (b)

FIGURE 9: (a) Sketch of the compliant mechanism and (b) with the vibration isolator

and the equations of motion of the mechanism with the isolator are

$$M_1\ddot{x}_1(t) + 2k_{lb}x_1(t) + k_{sb}\big(x_1(t) - x_2(t)\big) = F(t) \tag{6}$$

$$M_2\ddot{x}_2(t) + k_{sb}\big(x_2(t) - x_1(t)\big) = 0 \tag{7}$$

where M_1 is mass of the compliant mechanism, M_2 is the mass of the isolator, k_{lb}, k_{sb} are the spring constants of the long and short flexible beams, $\ddot{x}_i, x_i$ are the acceleration and position od the corresponding masses, x is the displacement of the base mechanism under the applied force *F(t), A* is the amplitude of the force and *ω* is the forcing frequency.

Solving Eqns. 6 and 7, the displacement of M_1 yields

$$x_1(t) = \frac{F(k_{sb}-M_2w_n^2)}{(2k_{lb}+k_{sb}-M_1w_n^2)(k_{sb}-M_2w_n^2)-k_2^2} \tag{8}$$

Since the goal is to dampen the oscillations on the primary cart (M_1) when it's forced at its own natural frequency ($\omega_n = \sqrt{2k_{lb}/M_1}$) , setting Eqn. 8 to zero gives the following ratio

$$\frac{2k_{lb}}{M_1} = \frac{k_{sb}}{M_2} \tag{9}$$

Once the original vibratory system is designed with a mass and two long beams, the secondary system parameters mass and stiffness can be determined using Eqn.9. The stiffness of the fixed free flexible beam is given in Eqn. 4, however, since we 3D print the springs using PLA, Young's Modulus (*E*) is not constant and changes with 3D printing settings. Keeping the same settings, we printed several long and short beams with different thicknesses, attached them to the mass and collected free-response data using an accelerometer, and plotted the power spectrum to determine the natural frequency and experimental stiffness. Also, since the only variable in the 3D printed springs were the thickness of the beams, the stiffness of cantilever beam equation can be rewritten as

$$k = \frac{3Ebh^3}{12L^3} \Rightarrow k = \frac{b}{4L^3}h^3\,E \Rightarrow k = Ah^3E \tag{10}$$

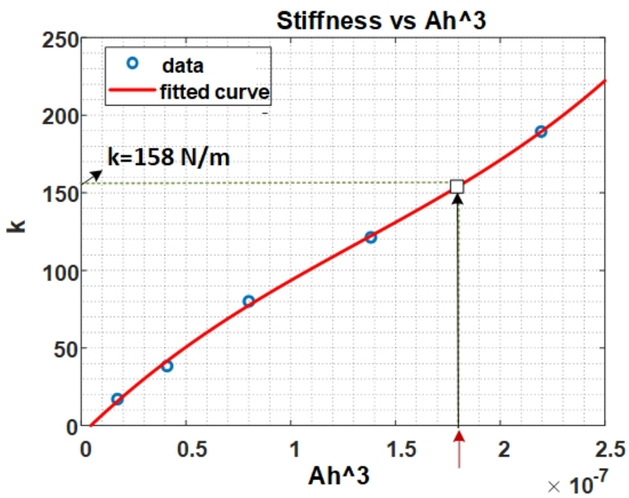


FIGURE 10: (a) Stiffness vs normalized geometry for short beam

Here, the constant A is the geometric constant, $b/4L^3$. Knowing the experimental stiffnesses and thickness of the beams, the slope of Eqn.10 gives the Young's Modulus as the data and a fit function for the short beams are plotted in Fig 10. For instance, if the normalized geometry (Ah^3) is 1.7×10^{-7}, then the stiffness is around 158 N/m. On the contrary, if one needs to 3D print a short beam with a stiffness of 200 N/m, then the normalized geometry is 2.3×10^{-7}. The width (b) and the length (L) of the short beam were 45 mm and 78 mm, so the thickness should be 2.1 mm. A 3rd order polynomial is fitted to the data as

$$k(z) = 5.8z^3 - 7.4z^2 + 63.3x + 92.88 \quad (11)$$

where z is the normalized geometry.

Students can design a primary system, calculate its natural frequency and excite the system at its own frequency reading the acceleration of the first mass using the accelerometer and available data acquisition. Later design a secondary mass (M_2) and spring (k_{sb}) satisfying Eqn. 9 to dampen the oscillations on the primary mass.

4. CONCLUSION

There is still a demand for design and development of educational laboratory equipment for undergraduate level engineering courses. In this study we developed 3, low-cost and portable vibratory mechanisms to be utilized in engineering dynamics and mechanical vibrations courses. The 3-pendulum system can be demonstrated in dynamics, cantilever beam with springs and compliant vibration isolator can be used in the vibrations and vibrations and control laboratories.

For future considerations, the equipment will be provided to the mechanical vibrations students along with their learning activities, and student feedback will be collected to improve the design.

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