Proceedings of the ASME 2021
International Design Engineering Technical Conferences and
Computers and Information in Engineering Conference
IDETC/CIE2021
August 17-20, 2021, Virtual, Online

DETC2021-XXXX

DESIGNING AND 3D PRINTING LAB EQUIPMENT FOR MECHANICAL VIBRATIONS COURSE AND LABORATORY

Josh Lewis
Kennesaw State University
Marietta, GA, USA

Benjamin Estrada
Kennesaw State University
Marietta, GA, USA

Paul Pena
Kennesaw State University
Marietta, GA, USA

Martin Garcia
Kennesaw State University
Marietta, GA, USA

Ayse Tekes
Kennesaw State University
Marietta, GA, USA

ABSTRACT

Undergraduate mechanical engineering students struggle in comprehending the fundamentals presented in an introductory level mechanical vibrations course which eventually affects their performance in the posterior courses such as control theory. One salient factor to this is missing the visualization of the concept with hands-on learning since the vibrations and control laboratory course is offered in the following semester. This study presents the design, development of three portable and 3D-printed compliant vibratory mechanisms actuated by a linear motor and their implementation in vibrations course and vibrations and control laboratory. The proposed setups consist of flexible and compliant springs, sliders, and base support. Mechanisms are utilized to demonstrate free and forced vibrations, resonation, and design of a passive isolator. In addition to the 3D-printed, portable lab equipment, we created the Matlab Simscape GUI program of each setup so instructors can demonstrate the fundamentals in the classroom, assign homework, project, in-class activity or design laboratory.

Keywords: portable laboratory equipment, 3d-printed design, demonstration of mechanical vibrations, Simscape GUI Program

1. INTRODUCTION

Keeping engineering students' momentum and interest in a class throughout the semester is challenging and often students lose their interest if they get overwhelmed with the highly mathematical concepts. In many institutions, students are taught the fundamental concepts of undergraduate level engineering courses in a traditional manner where the instructor presents the topic and supports the material with class projects and homework. Although active learning has been touted to have a significant effect on improving student understanding of the fundamental topic, the vast majority of the engineering courses are taught in a traditional way in which instructors present the topic without any class-activity [1,2]. A preponderance of research shows that in passive learning students fail to apply their knowledge to an engineering application thereby missing the fundamentals and course learning objectives [3-5]. As opposed to passive learning, in active learning students are given more opportunities for class engagement keeping them more connected to the presented topic and create their understanding. Although active learning has been proven to have significant improvement in student understanding, adopting learning learner-centered teaching in major engineering courses is not a simple task that requires extra effort [6]. The instructor can create in-class activities requiring more student participation and also utilize technology to demonstrate or visualize the abstract concept. Considering the engineering faculties' workload, and research requirements, faculty might not find enough time to create activities for the courses.

Due to the nature of mechanical engineering, students taking remedial or major courses find the topics complex and heavily mathematical especially for students who still struggle in math. Since freshman and sophomore courses focus mainly on theory, students might lose sight of the core of the subjects if they don't comprehend the mathematical derivations.

Mechanical vibrations is one of the major courses students take as a junior and also prerequisite to introductory level control theory and vibrations and control laboratories which are often taken in the following semester or year. Unlike electrical/mechatronics engineering courses, mechanical engineering courses don't have laboratory sections as part of the offered courses. Since mechanical engineering students take the vibrations and control laboratories in the following semester, they find it difficult to remember the concepts from mechanical vibrations course such as modeling of single degree of freedom (SDOF) and multi degrees of freedom translational and rotational vibratory systems, basic concepts such as resonation, beating, vibration modes, and vibration isolation. Senior level mechanical engineering students taking the machine dynamics and vibrations laboratory are expected to derive the equations of motion of educational laboratory systems, conduct experiments, collect data and perform system characterization to calculate the unknown parameters using the concepts from the mechanical vibrations course. In many cases due to the aforementioned reasons students fail to remember the vibrations theory.

There has been an increased interest in the design and development of portable and affordable laboratory equipment for control theory courses and laboratories mainly for the electrical engineering program. Reck developed a portable kit with Raspberry Pi to study state-space modeling of inverted pendulum controlled by a DC motor [7]. Similarly, a low-cost PID temperature control lab equipment was designed for biomedical engineering students [8].

We believe that if students are provided hands-on, mode-eliciting activities in the vibrations course while teaching the topic, they will gain a thorough understanding while keeping their momentum and interest for the course throughout the semester. Since the laboratory equipment accommodated in the vibration's laboratories are heavy and also integrated with their own software, instructors can't take it to the classroom or provide it to the students as a take-home project or homework. With the advent of new technologies such as additive manufacturing, we developed several 3D-printed laboratory equipment for dynamics, vibrations, and control theory courses along with their associated laboratories. A 3D-printed compliant parallel-arm mechanism integrated with several compliant fixed-free beams and a mass was developed, acceleration data was recorded using ADXL-335 accelerometer and Arduino for system characterization. In-class activities and laboratory exercises along with student feedback were shared in [9]. A 3D-printed torsional system consisted of two disks, a rod, and a potentiometer to study SDOF and 2 DOF free-response analysis and modeling were developed for vibrations course and laboratory in [10]. 2 DOF compliant vibratory mechanism was designed, 3D-printed in polylactic acid (PLA), actuated by a DC motor while reading the displacement of the two carts through a laser displacement sensor was developed in [11].

As an alternative to portable laboratory equipment to provide more hands-on experience, visual graphical user interface (GUI) programs can also be utilized to demonstrate fundamental topics.

In this study, we present the design of three novel, portable and low-cost 3D printed vibratory mechanisms consisted of flexible beams, masses, frame, linear motor, and accelerometers. The instructor can carry the equipment to the classroom to demonstrate the free and forced response of SDOF to the 3 DOF system while plotting the response of the system through external NI DAQ/Arduino and Matlab only in 10 minutes and assign homework for system identification. If multiple setups of the mechanisms are created, then the portable vibratory mechanisms can be utilized in the vibrations and control laboratories. In addition to the experimental setup, the Matlab Simscape GUI program is developed to visualize the same concept and find the geometry of the 3D printed springs for a specific stiffness. The CAD model of the mechanisms, in-class activities, and laboratory handouts are open sources and shared publicly.

The rest of the paper is organized as follows. The design and development of the mechanism are presented in Section 2, the design of the Matlab Simscape GUI program is described in Section 3, theoretical background, in-class, and laboratory activities are provided in Section 4, and concluding remarks are summarized in Conclusion.

2. PORTABLE LAB EQUIPMENT DESIGN

This section briefly presents the design and experimental setup of two compliant parallel arm mechanisms and a rectilinear compliant vibratory system.

2.1 3-DOF Compliant Parallel Arm Mechanism

The compliant parallel arm mechanisms are designed in horizontal and vertical configurations. The horizontal compliant parallel-arm mechanism consists of 3 masses, 8 flexible fixed-free beams having various thicknesses, and support. The pin connection between the linear motor and the primary mass allows imparting force to the primary mass while reading acceleration data from ADXL 335 accelerometers from each mass. All parts of the mechanism are 3D printed in Polyethylene

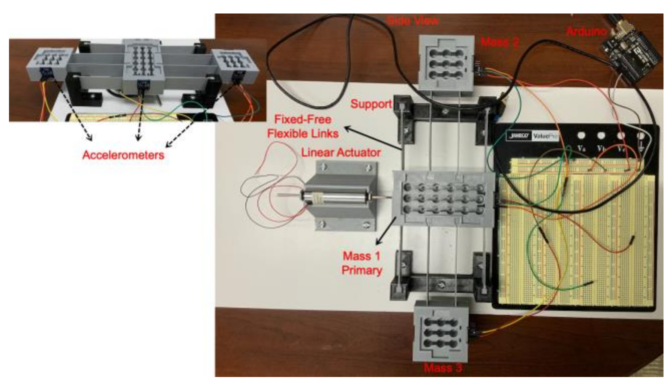

FIGURE 1: Experimental setup of the (a) horizontal and (b) vertical (bottom) compliant parallel arm mechanism

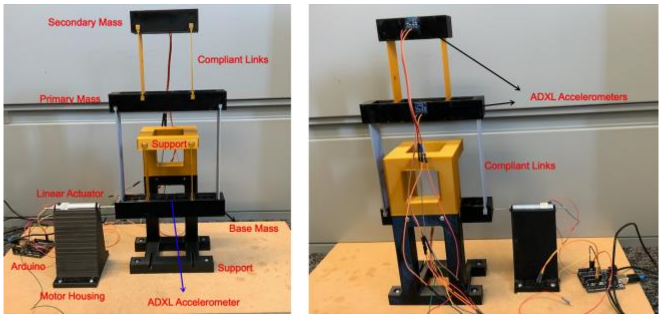

FIGURE 2: Front and back view of the vertical compliant isolator resonator mechanism

Terephthalate Glycol (PETG) as the experimental setup is depicted in Fig 1. Although acceleration can be acquired from Arduino, external NI DAQ can also be utilized as an alternative.

The vertical setup is comprised of a base, primary and secondary system. The primary mass which is subjected to the loading through a linear motor is connected to the base via two flexible links, the secondary system is designed to isolate the vibrations on the primary system using additional two flexible links. All parts are 3D printed in PETG, three ADXL 335 accelerometers are attached to the masses. The linear actuator is controlled by Arduino while the acceleration data can be recorded through Arduino or external NI DAQ as the setup is shown in Fig 2. Different configurations of the vertical compliant resonator/isolator mechanism can also be created by changing the number of compliant links connected between the support and the base mass as an alternative setup is shown in Fig. 3.

The total cost of both vertical and horizontal setups is around $550 mainly due to the cost of the linear actuator and the motor driver since the 3D printing cost is very small if one has a home type 3D printer and PETG filament.

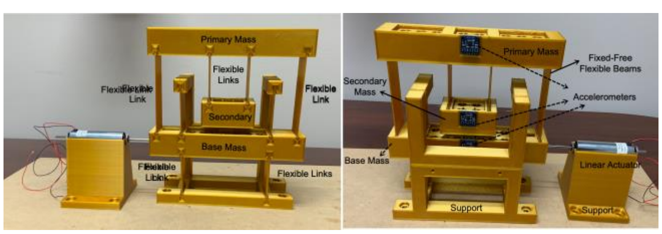

FIGURE 3: Front and back view of an alternative vertical setup

2.2 2-DOF Compliant Rectilinear Mechanism

The prevailing translational vibratory mechanisms utilized in the vibrations and control laboratories mainly consist of sliders, rail, dashpots, actuators, and compression springs. It's easy for students to identify spring elements in such cases. However undergraduate students struggle in identifying the spring elements in a vibratory mechanism when the system integrates flexible members rather than mechanical springs. With a focus on demonstrating the fact that any flexible component in a mechanism serves as a spring, we designed a

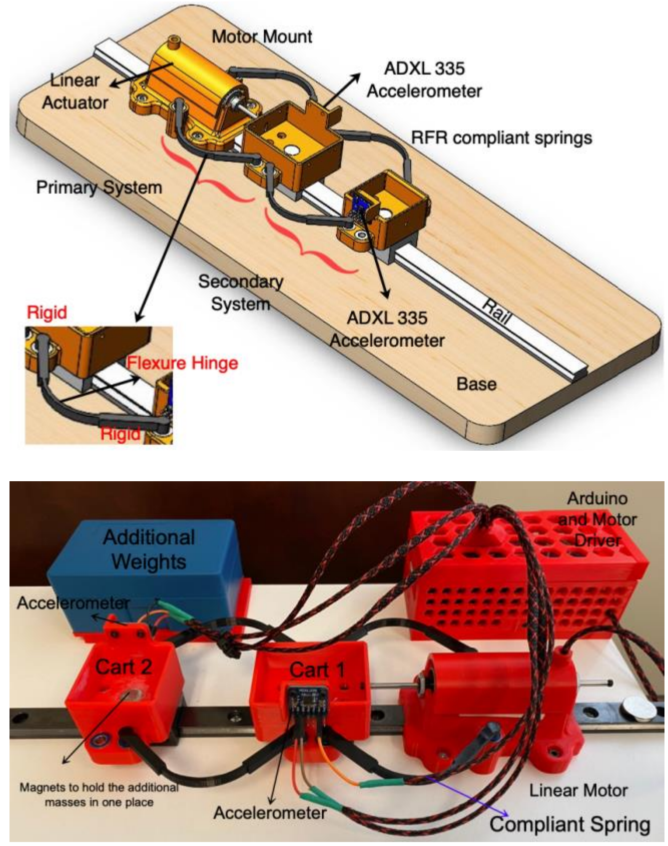

FIGURE 4: Cad model (top) and Experimental setup (bottom) of the compliant vibratory mechanism

translational, compliant vibratory mechanism which is consisted of two sliders, rail, linear motor, and compliant links. Since compliant members deflect when subjected to loading while continuously storing and releasing energy, this makes them ideal for the replacement of mechanical springs. The rail and the carts are purchased from Misumi, and additional bases holding the accelerometers and springs are 3D printed in polylactic acid (PLA). Rigid arm-flexure-rigid arm (RFR) springs possessing various flexure hinge thicknesses are 3D printed in PETG and pinned to the additional bases using ball bearings as shown in Fig. 4. Circular magnets are glued to the sliding carts to change the mass by attaching additional loads varying from 20 mg to 100 grams. Since the stiffness of the RFR springs mainly depends on the thickness of the flexures, students can design, and 3D print a spring with the desired stiffness in 20 minutes if they have a 3D printer.

3. MATLAB SIMSCAPE GUI DESIGN

It's challenging for undergraduate engineering students to obtain the dynamical model of multi-degree of freedom vibratory mechanisms. In order to visualize the fundamental concepts using the proposed 3D printed laboratory equipment discussed in the former section, the Matlab Simscape GUI program is developed. The Simcape model of mechanical systems can be created using the blocks provided in the library

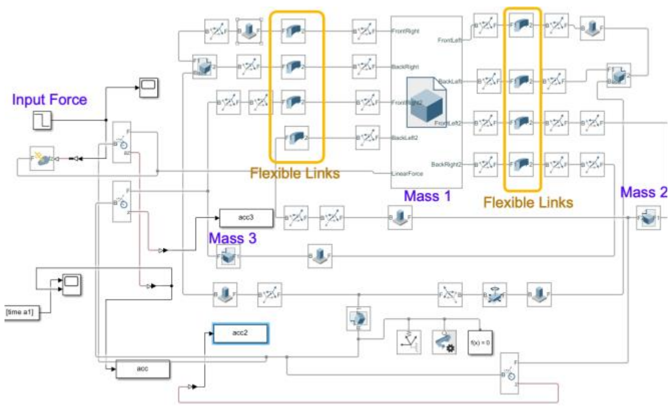

FIGURE 5: Simscape GUI program for horizontal compliant parallel arm mechanism

or by importing the assembly cad model. If the blocks in the library are used for creating the flexible links or compliant flexures, then discrete beam elements should be selected.

3.1 Simscape GUI Program for Compliant Parallel Arm Mechanism

The developed GUI program not only helps students visualize the concept but also helps them design springs for a desired stiffness and system behavior. The cad model of the horizontal parallel-arm mechanism is imported in a new Simulink model, flexible links are replaced with slender bodies having elastic deformation capabilities and connected to the masses using rigid transform-weld joint pairs on both connecting points as illustrated in Fig.5. The stiffness and inertia of each flexible link are defined using the corresponding material properties.

Students can study free and forced response analysis of the compliant parallel-arm mechanism by selecting the input. If an impulse force in the form of a dirac function (δ(t)) is created using either signal builder or step function which should be implemented for a very short time, yielding free response, students can perform system identification to find the unknown parameters of the system such as its equivalent stiffness and damping. The acceleration of the carts and simulation data are recorded using the ToWorkspace blocks in the array formatting. The natural frequencies of the presented 3 DOF mechanism can be calculated from the free-response data using the code embedded in the GUI program.

To mimic the linear actuator, force input can be selected as a harmonic function, $f(t) = Asin(wt)$, where A is the amplitude and ω is the frequency of oscillations. Alternatively, a sweep signal can also be applied to change the input frequency

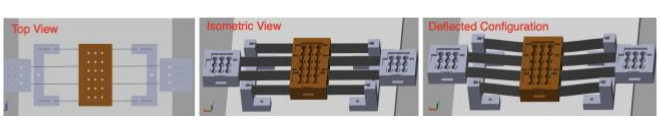

FIGURE 6: Top view, isometric view and deflected configuration of the compliant parallel arm Simscape GUI mechanics explorer

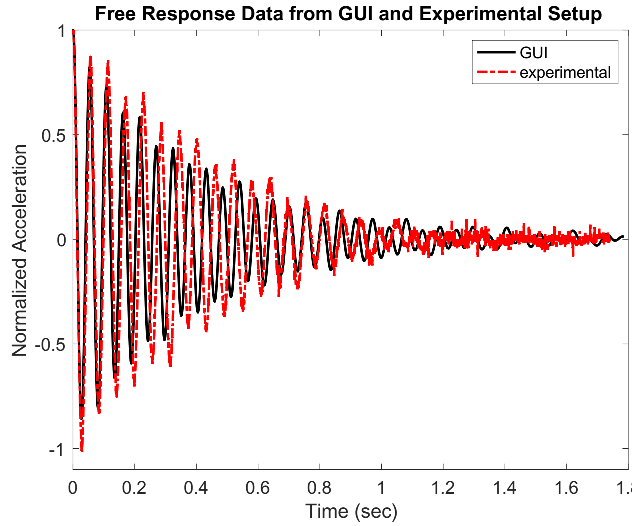

FIGURE 7: Normalized acceleration data (acceleration/ max(acceleration)) obtained from the simcape GUI and the experimental setup

from 1 Hz to 14 Hz similar to the actual system. The GUI program allows students not only to change the input force and record output position, velocity, or acceleration of the carts but also to change the mass and material properties of the flexible beams.

Once the GUI is run either for a free or forced response, the mechanics explorer visualizes the motion of the compliant parallel-arm mechanism helping students to observe the characteristics as shown in Fig. 6.

The acceleration data from the experimental setup and the GUI program are compared as seen in Fig. 7. Both data match well validating the Simscape GUI model. The discrepancies are due to the 3D printing. Material properties defined for the flexible beams are slightly different from the theoretical values. Also, Young's modulus and density of the material are induced by the selected infill percent, and pattern in 3D printing.

3.2 Simscape GUI Program for Compliant Vibratory Mechanism

A new GUI program utilizing the Simscape library blocks is created for the compliant vibratory mechanism. Since the cad model is not required, this gives the user more flexibility to change the system parameters. SDOF compliant mechanism consisted of a cart sliding along the horizontal direction connected to support through the RFR compliant links is designed as shown in Fig. 8. If the user double clicks on the

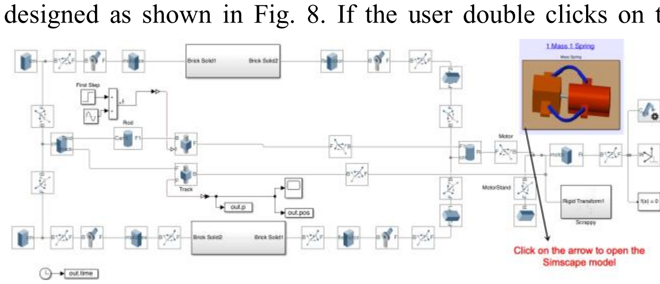

FIGURE 8: Matlab Simscape GUI model of the SDOF compliant vibratory mechanism

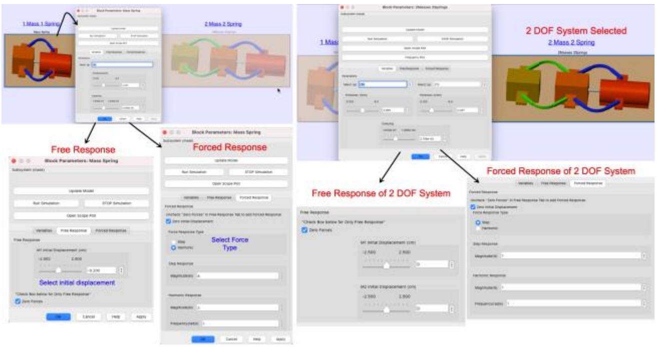

FIGURE 9: Changing the settings of SDOF and 2 DOF compliant vibratory mechanism

SDOF model, then a new window allowing the user to enter parameters such as the mass of the slider along with the thickness and damping of the flexure on the RFR linkage while keeping the rigid arm lengths constant. Similarly, the Simscape model of the 2 DOF system is also created. For both systems, the user can either select the free-response by displacing the cart(s) to the right or left at a maximum distance of 2.5 cm using the slider or simply by typing the initial displacement inside the box or perform forced response simulations as illustrated in Fig. 9. Students can also export simulation time, position, velocity, and acceleration of the carts as well as plotting the responses through the scope embedded in the settings window.

Case Study: A SDOF primary mechanism is designed such that the mass is 136 grams, and the thickness of the flexure is 2.6 mm. The experimental system is designed with the same parameters and free-response data is collected by displacing and releasing the cart. As seen from Fig. 10, both data match well validating the Simscape GUI program response.

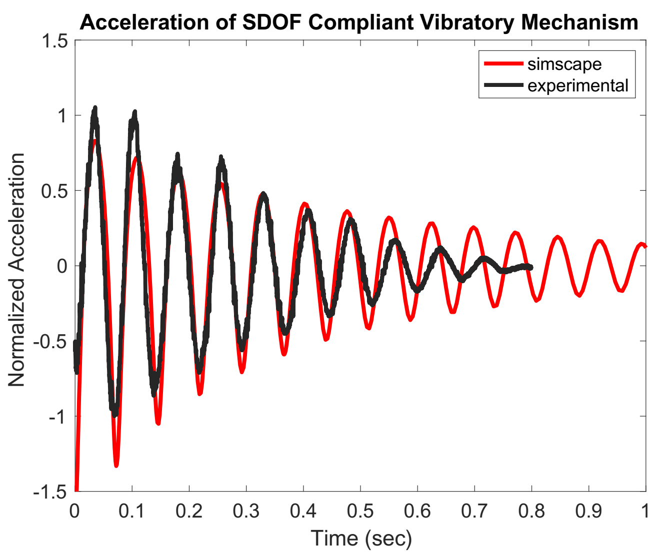

FIGURE 10: Comparison of the acceleration data from SDOF compliant parallel arm mechanism.

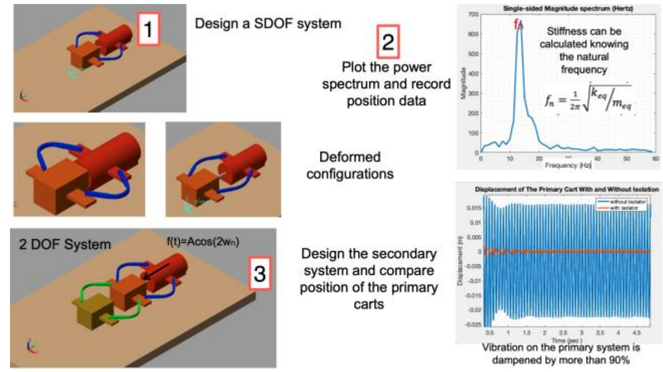

FIGURE 11: Demonstration of the design of a vibration isolator using a secondary mass-spring system

The natural frequency of the SDOF is calculated as 13.76 Hz and knowing the mass of the cart and natural frequency, the equivalent stiffness is calculated as 1016.6 Nm/rad and since the springs are connected in parallel, the stiffness of a single RFR compliant link yields 508 Nm/rad as illustrated in Fig. 11.

4. THEORY AND LEARNING ACTIVITIES

Mechanical vibrations which is a branch of dynamics is one of the major course mechanical engineering students are required to take for graduation. This 3-credit course covers the modeling of SDOF to 2 DOF free and forced response analysis, finding equivalent mass, damping, and spring constant of machines/mechanisms, determination of natural frequencies, vibration amplification, vibration isolation, and vibration control. Although the course starts with a simple SDOF mass-spring-damper system tied to the dynamics course, the vast majority of the students struggle in obtaining the equations of motion, finding the lumped model, calculating the response of the system for a given input as well as the calculation of the natural frequencies. Doing by learning has a strong impact in comprehending the abstract topics however mechanical engineering students need to wait for another semester for the vibrations and control theory laboratory course.

The learning objectives of the in-class and laboratory activities of the developed portable mechanisms can be enumerated as (1) deriving the equation of motion of SDOF- 3 DOF translatory mechanism, (2) finding the equivalent stiffness and natural frequency using theory, (3) obtaining the natural frequency experimentally, (4) calculating the stiffness experimentally, (5) system identification, (6) comparison of an experimental setup and simulated model in Matlab Simulink, (7) passive isolator design and (8) vibration control.

4.1 Theoretical Background for 3 DOF Compliant Parallel Arm Mechanism

The sketch of the horizontal compliant parallel-arm mechanism is illustrated in Fig. 12. Since each mass has only SDOF, the equations of motion can be obtained using the mass-matrix method. If only natural frequencies are of interest, then

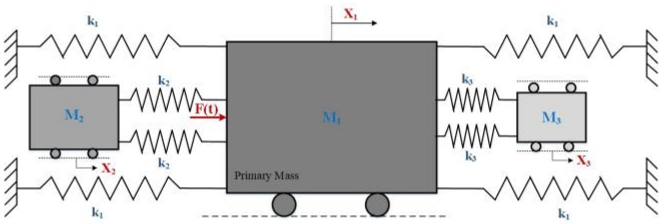

FIGURE 12: Sketch of the horizontal compliant parallel arm mechanism

the damping and applied force can be neglected. Mass-matrix form of the horizontal mechanism in the form of

$$[M][\ddot{x}(t)] + [K][x(t)] = [0] \tag{1}$$

yields

$$\begin{bmatrix} M_1 & 0 & 0 \\ 0 & M_2 & 0 \\ 0 & 0 & M_3 \end{bmatrix}\begin{bmatrix} \ddot{x}_1 \\ \ddot{x}_2 \\ \ddot{x}_3 \end{bmatrix} + \begin{bmatrix} 4k_1 + 2k_2 + 2k_3 & -2k_2 & -2k_3 \\ -2k_2 & 2k_2 & 0 \\ -2k_3 & 0 & 2k_3 \end{bmatrix}\begin{bmatrix} x_1 \\ x_2 \\ x_3 \end{bmatrix} = \begin{bmatrix} 0 \\ 0 \\ 0 \end{bmatrix} \tag{2}$$

where M is the mass matrix, K is the stiffness matrix and k_i , M_i , x_i , $\dot{x}_i$, $\ddot{x}_i$ are the spring constant, mass, position, velocity, and acceleration of the corresponding carts respectively. Since

$$\ddot{x}(t) = -\omega^2 x(t) \tag{3}$$

in which ω is the natural frequency. Knowing the numerical values of the system parameters, students can calculate the theoretical natural frequencies by simply finding the determinant of

$$\det([K - Mw^2]) = [0] \tag{4}$$

They can also plot the power spectrum by writing a simple code in Matlab after importing the experimental data in Matlab workspace and compare the natural and experimental frequencies and discuss the reasons for any discrepancy.

For system characterization, system parameters can be calculated from the free-response data. The free-response data can be collected by displacing the primary cart at a distance

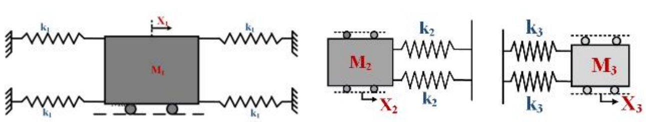

FIGURE 13: Three main systems forming the horizontal compliant parallel arm mechanism: primary, secondary and third system respectively

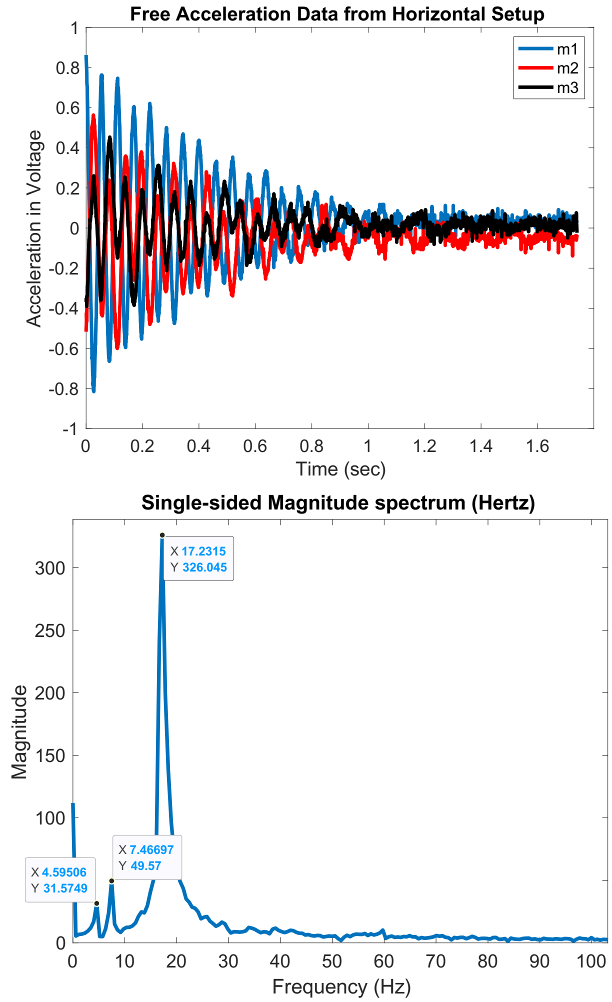

FIGURE 14: Free response acceleration data and power spectrum from the horizontal setup

while recording acceleration from the accelerometers. Before assembling the system, acceleration vs time data for each subsystem can be recorded, and the power spectrum can be plotted to determine the experimental natural frequencies as the sketches for each system are shown in Fig. 13. For the same example system, the natural frequencies of each setup were obtained as 17.23 Hz, 7.46 Hz, and 4.59 Hz respectively as seen in Fig. 14. Since natural frequency is $\omega_n = \sqrt{k_{eq}/m_{eq}}$, and the primary, secondary and third systems have an equivalent stiffness of $4k_1, 2k_2, 2k_3$, masses are 0.97 kg, 0.047 kg, and 0.12 kg. Using experimental data and the logarithmic decrement method, the damping constant of each system can also be obtained.

The sketch of the vertical compliant parallel-arm mechanism is shown in Fig. 15. The equations of motion of the system including the damping effects are

$$m_1\ddot{x}_1 + (c_1 + c_2)\dot{x}_1 + (k_1 + k_2)x_1 - c_2\dot{x}_2 - (k_1 + k_2)x_2 = f(t) \tag{5}$$

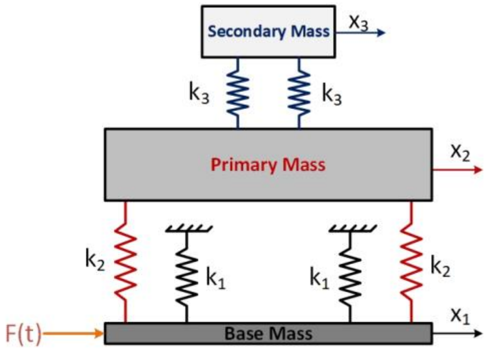

FIGURE 15: Sketch of the vertical compliant parallel arm mechanism

$$m_2\ddot{x}_2 + (c_1 + c_2)\dot{x}_2 + (k_2 + k_3)x_2 - c_2\dot{x}_1 - c_3\dot{x}_3 - k_2x_1 - k_3x_3 = 0 \quad (6)$$

$$m_3\ddot{x}_3 + c_3\dot{x}_3 + k_3x_3 - c_3\dot{x}_2 - k_3x_2 = 0 \quad (7)$$

Since the symmetry of the fixed-free flexible beams are taken with respect to its free end as illustrated in Fig. 16, the theoretical stiffness of each beam is defined as

$$k_{theoretical} = \frac{EI}{L^3} \quad (8)$$

where E is the Young's Modulus, I is the inertia, and L is the length. Free response data can be recorded through either Arduino or external NI DAQ for system identification. The logarithmic decrement method is exploited to calculate the damping constant acting on each system, damped frequency, natural frequency, and stiffnesses of springs. Students can compare the theoretical stiffnesses with the experimental values.

The Simulink model can be created using the three equations as shown in Fig. 17. Both simulated and experimental data can be plotted together to validate the calculated parameters.

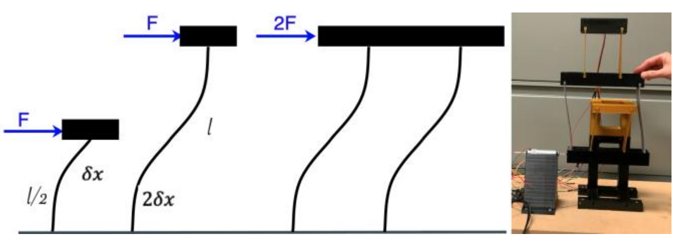

FIGURE 16: A fixed-free beam, arm, and the compliant parallel arm

4.1 Learning Activities Using 3D Printed Lab Equipment and Simscape GUI Programs

The developed stand-alone and open-source Simscape GUI programs serve as a great visualization tool for a quick demonstration for both face to face and online mechanical vibrations courses. The instructor can simulate the two mode shapes of a MDOF system by adjusting the initial displacements so that the masses will be oscillating at the same frequency, vibration isolation, resonation, beating, and free and forced responses.

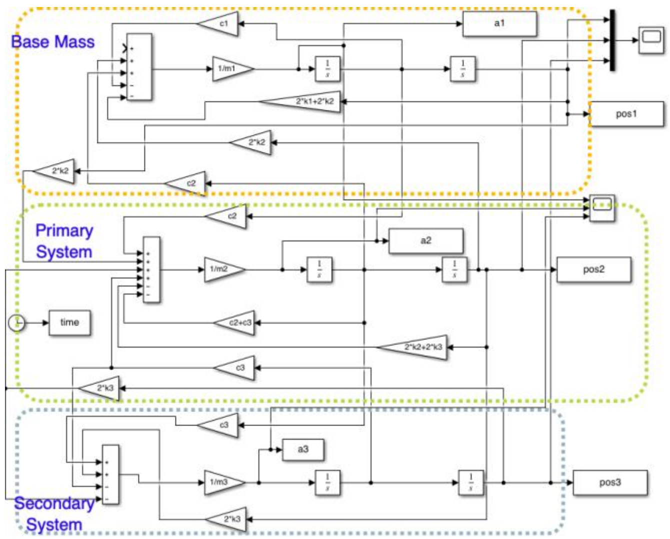

FIGURE 17: Matlab Simulink model of the vertical compliant parallel arm mechanism

The instructor can also discuss the following preliminary questions before simulating the systems: What are the three parts of a vibratory mechanism, suggest a method determining the damping constant of an underdamped system, and why is it important to find the natural frequency of a system.

The portable laboratory equipment can be utilized both in the vibrations course and vibrations and control laboratories. If multiple of the same setups are built, then each team of students can work on their setup and configurations. Since parts of the mechanisms are separate, students first build their system, connect and power the sensors, conduct experiments, acquire data for further analysis in Matlab, and use the experimental data for system identification.

5. CONCLUSION

This study presents the design and development of three portable, compliant vibratory systems for the mechanical vibrations course and vibrations and control laboratory. The parts of the mechanism are 3D printed using PLA and PETG filaments. Stand-alone, open-source Simscape GUI programs for the horizontal parallel arm and the compliant vibratory mechanism are created for a quick demonstration in the class and also stiffness calculation of the flexible links and compliant RFR springs. Learning objectives that can be covered using the low-cost, portable, and 3D printed laboratory equipment and the Simscape GUI program are discussed.

For future considerations, laboratory equipment and Simscape GUI program will be provided to the junior and senior mechanical engineering students taking vibrations and vibrations and control theory courses and student feedback will be solicited to improve the current designs.

ACKNOWLEDGEMENTS

This research is supported by the National Science Foundation under Grant No. 2002350.

REFERENCES

[1] Mehdi, and Cindy Gunn. "Toward better learning opportunities for undergraduate mechanical engineering students: A case study." International Journal of Mechanical Engineering Education (2019): 0306419019858099.

[2] Blumberg, Phyllis. Developing learner-centered teaching: A practical guide for faculty. John Wiley & Sons, 2008.

[3] Minhas, Paras Singh, Arundhati Ghosh, and Leah Swanzy. "The effects of passive and active learning on student preference and performance in an undergraduate basic science course." Anatomical sciences education 5, no. 4 (2012): 200-207.

[4] Chi, Michelene TH, and Ruth Wylie. "The ICAP framework: Linking cognitive engagement to active learning outcomes." Educational psychologist 49, no. 4 (2014): 219-243.

[4] Menekse, Muhsin, Glenda S. Stump, Stephen Krause, and Michelene TH Chi. "Differentiated overt learning activities for effective instruction in engineering classrooms." Journal of Engineering Education 102, no. 3 (2013): 346-374.

[5] Baba, Khalid, and Nicolas Cheimanoff. "A Comparative Study of Active and Passive Learning Approaches in Hybrid Learning, Undergraduate, Educational Programs." In Science and Information Conference, pp. 715-725. Springer, Cham, 2020.

[6] Magana, Alejandra J., Camilo Vieira, and Mireille Boutin. "Characterizing engineering learners' preferences for active and passive learning methods." IEEE Transactions on Education 61, no. 1 (2017): 46-54.

[7] Reck, Rebecca M., and R. S. Sreenivas. "Developing an affordable and portable control systems laboratory kit with a Raspberry Pi." Electronics 5, no. 3 (2016): 36.

[8] Oliveira, Paulo Moura, and John D. Hedengren. "An APMonitor temperature lab PID control experiment for undergraduate students." In 2019 24th IEEE International Conference on Emerging Technologies and Factory Automation (ETFA), pp. 790-797. IEEE, 2019.

[9] Tekes, Ayse, Kevin Van Der Horn, Zach Marr, and Chong Tian. "Dynamics, vibrations, and control lab equipment design." In Dynamic Systems and Control Conference, vol. 51906, p. V002T16A001. American Society of Mechanical Engineers, 2018.

[10] Tekes, Ayse. "3D-printed torsional mechanism demonstrating fundamentals of free vibrations." Canadian Journal of Physics 99, no. 2 (2021): 125-131.

[11] Tekes, Ayse, Tris Utschig, and Tyler Johns. "Demonstration of vibration control using a compliant parallel arm mechanism." International Journal of Mechanical Engineering Education (2019): 0306419019887140.

[12] Giannakakos, Niko, Ayse Tekes, and Tris Utschig. "2 DOF Compliant 3D-PLE System Demonstrating Fundamentals of Vibrations and Passive Vibration Isolation." In ASME International Mechanical Engineering Congress and Exposition, vol. 84577, p. V009T09A002. American Society of Mechanical Engineers, 2020.

