Original article

IJMEE

International Journal of Mechanical Engineering Education
1–20

DOI: 10.1177/03064190221085038
journals.sagepub.com/home/ijj
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Reinforcing student learning by MATLAB simscape GUI program for introductory level mechanical vibrations and control theory courses

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Abstract

The highly mathematical nature of introductory level vibrations and control theory courses results in students struggling to understand the concepts. Hands-on activity demonstrated in class can help them better understand the concepts. However, there is still an ongoing effort to lower the currently substantial cost of educational laboratory equipment for undergraduate-level engineering courses. Also, with the COVID-19 crisis, the Spring 2020 academic year took an unexpected turn for academics and students all over the world. Engineering faculty who teach laboratories had to move online and instruct from home. Online course preparation takes more time and effort compared to traditionally designed face-to-face courses and was compounded considering the unprecedented situation where many instructors didn't have time to record data from existing lab equipment or record video in their laboratories. In this paper, we present a Matlab Simscape GUI program designed to simulate modeling and control of dynamical systems for vibrations and control theory courses, and their associated laboratories, as one potential solution for online instruction. To complement the simulation program, online classroom and homework activities were designed using a learning sciences approach connecting several critical educational theories which can bolster student motivation, engagement with the material, and overall learning performance. The simulation is presented along with data from 19 students who completed the

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associated classroom and homework activities. Survey results probing student perceptions about the value of the learning tasks for the simulation were overwhelmingly positive and indicate this approach holds promise in supporting student learning.

Keywords
fundamentals of vibrations, control theory, simulation and analysis, virtual laboratories, Matlab Simscape

Introduction

In many institutions, limited resources for laboratory equipment inhibit student learning of dynamics, vibrations, and control concepts due to constraints on the use of available turnkey equipment. As a result, the laboratory components for these courses are often limited as the equipment is expensive, few in number, and bulky.[1] Nonetheless, providing hands-on physical experiences in class and lab can enhance student learning through applications of these highly complex theoretical concepts.[2] Beneficial outcomes include constructing deeper knowledge, skills for modeling and designing experimental systems, developing technical laboratory skills, and skills in analyzing acquired data, interpreting results, and presenting.[3] Although laboratories are essential in undergraduate engineering courses, the challenges for student learning that arose with the COVID-19 crisis and which we still face have made it much more difficult to achieve course learning objectives tied to laboratory or hands-on experiences. With the global crisis, the Spring 2020 academic year took an unexpected turn for academics and students all over the world when faculty had to move online and instruct from home. Faculty who teach face-to-face lab sections were not prepared for the quick transition to online labs. Further, preparation for remote instruction takes more time and effort compared to traditionally designed face-to-face courses, especially considering the unprecedented situation we face now with the many or even all students continuing to learn online. However, it is still true that engineering labs require plenty of hands-on learning.

Teaching undergraduate level dynamics, vibrations, and control theory courses, we realized an opportunity to address some of the gap in hands-on experiences through visualization of basic conceptual principles while the topic is introduced in the classroom. The vast majority of undergraduate students struggle with highly mathematical abstract topics.[2,4] In many institutions, laboratories associated with the vibrations and control classes in mechanical engineering are offered in the subsequent semester. This is unlike other programs such as electrical, computer and, mechatronics engineering where many of the courses in these programs have laboratories integrated as part of the courses where students learn the fundamentals in the beginning and continue with hands-on activities before starting a new topic. Since mechanical engineering students generally take the laboratories in the next or following semesters, many not only fail to remember the essential topics but also lose their interest.[1,5] Visualization in class can address that issue.

In our previous work, we designed, developed, and implemented several 3D printed, portable laboratory equipment devices that are compact and low-cost to demonstrate the fundamentals of vibrations in class.[5] The instructor can bring the portable lab equipment into the classroom, conduct the experiment, collect data from the vibratory mechanism, and plot the response of the system while showing the mechanism behavior to the students in about 10 min.

In the online environment, while results of simulations can be demonstrated by the instructor in the classroom using commercially available software, some students find it difficult to fully comprehend, link, and visualize how the physical movements associated with the fundamental phenomena relate to theory. In some cases, students can control the actual equipment through the internet in remote labs. For example, Song et. al. developed a remote lab to control the vibrations on a mechanical system using actuation by smart materials.[10] Virtual laboratories have been found to improve students' knowledge and academic performance while decreasing geographic and financial constraints and have been part of active learning to reinforce student understanding. In an online lab, the parameters of the system are manipulated, and the simulation results are observed to gain insight into the underlying physics and the relation between the system variables. They have the potential to increase student learning while offering potential advantages that traditional laboratory environment cannot.

In our case, to meet the needs of visualizing the course concepts, a user-friendly MATLAB Simscape graphical user interphase (GUI) program that is customized for introductory level dynamics, vibrations, or control theory lecture courses has been developed to improve student's learning and performance outcomes. Applications in a laboratory course are also possible. The program allows the user to study single degree of freedom (SDOF) and multi degrees of freedom (MDOF) free and forced vibrations, position control of a pendulum-cart system, and trajectory control of a SDOF rectilinear system. The novelties of our GUI application are several. First, since it will be open source, anyone can download the program and use it as a stand-alone application on a local computer without the requirement of prior knowledge or experience of using the Simscape toolbox. Second, to the best of our knowledge, this is the first user interface program designed for mechanical vibrations and control theory courses using MATLAB Simscape. Third, the program combines several concepts in one package for extended learning using the same system. Fourth, the simulation is combined with a learning activity designed by applying an adapted version of Hanson's Activity Design Methodology[11] used in (Process Oriented Guided Inquiry Learning) POGIL settings. This model includes identifying the "why"[12] for an activity that directly addresses task value, and the model builds expectancy for success using a scaffolded approach.[13] The presented open-source GUI app can advance student learning and engagement by helping them develop a "feel" for the concepts introduced in lecture courses through virtual labs using MATLAB Apps.

The structure of the paper is as follows. Section 2 presents the components and structure of the MATLAB Simscape GUI program. While the GUI program can be utilized to demonstrate several fundamental, abstract topics covered in undergraduate-level vibrations and control theory courses, we chose three case studies to illustrate this capability, as presented in Section 3. Student survey results from the free and forced response studies are discussed in Section 4. Finally, we present concluding remarks about the value of this work and future research which may emerge as a result.

Design

Matrix laboratory (MATLAB) is a commercially available multi-paradigm numerical simulation and programming software favorably utilized by engineers. Students have free access to MATLAB in many engineering institutions, and an introductory level MATLAB coding class is frequently offered to freshmen. The program incorporates several toolboxes such as Simulink, Simscape, Symbolic, control design, and System identification. The proposed GUI program was created mainly using the Simulink and Simscape toolboxes. The mass-spring systems in each module allow students to analyze the system behavior for a user-defined mass, stiffness and damping constant. The vibratory mechanisms consist of carts employed as sliders whose motion is affected by surface friction and compression springs. The designed systems can be displaced to any position between -3 cm and $+3$ cm for free-response analysis, or an external force in the form of a step or sinusoidal signal can be applied to the primary cart for forced analysis. The Simulink package in the MATLAB software uses a schematic type diagram workspace. The diagram environment contains certain blocks that represent either mathematical functions or the Simscape Multibody blocks to represent physical objects as depicted in Figure 1.

One of the benefits of utilizing Simscape and Simulink is the 3D visualization that can be viewed in the MATLAB window under the Mechanics Explorer tab. When the Mass-Spring-Damper Simulink model is executed, it is visually displayed on the MATLAB window as shown in Figure 2.

For the design of a SDOF mass-spring-damper system, a world frame, solver configuration, and mechanism configuration blocks are dragged from the library to a new Simulink model. The world frame-block acts as an origin location that represents the location of the model with respect to the ground or world. The solver configuration

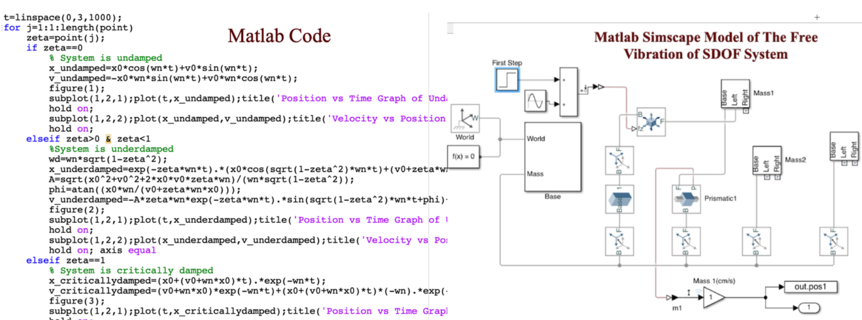

Figure 1. MATLAB code and Simulink diagram of the SDOF system under free vibration.

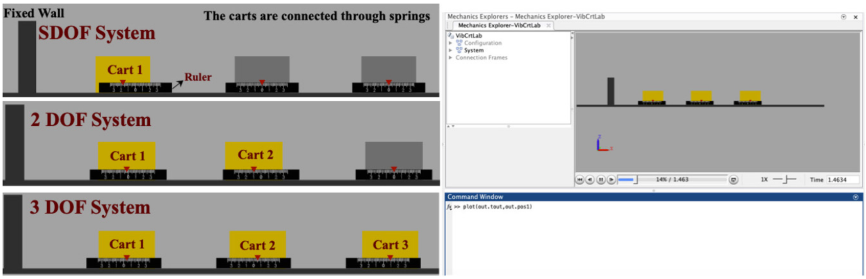

Figure 2. Mechanics explorer tab for SDOF and multi-degrees of freedom systems and how the mechanics explorer animates the motion when docked to the command window.

block in MATLAB Simulink allows the model to run certain solvers such as ode45 in calculating system behavior for the desired simulations. The mechanism configuration allows the user to select the target mechanism and define the gravitational acceleration and linearization delta. These blocks are typically connected to the first cart (slider) with respect to the world. A brick solid block with [x, y, z] coordinate dimensions is defined and is connected to the required block. To create a fixed wall so that the mechanical springs are fixed from one end, an additional brick solid block is used and connected to the platform which is placed in a certain position using a rigid transform block. Since there are no visual springs in the Simscape library, a joint is used in connecting the mass to the wall. Joints are blocks that allow certain motion in conjunction with another 3D block or mass. For example, a revolute joint in the library allows for relative rotational motion between a shaft and bearing. Cart 1 is connected to the platform and is limited to slide only along the horizontal axis; thereby a prismatic joint is used to translate cart 1 without any rotation. The prismatic joint serves as a track or rail that restricts cart motion to one direction. To connect cart 1 to the fixed wall, a cartesian block joint is utilized. The Cartesian joint block allows translation motion but restricts any rotation along all axes. These translation joint blocks allow the opportunity to include a spring stiffness, damping, and actuation forces required to simulate the motion of the system. Additional Simulink diagrams are employed to create models with up to three masses with different spring configurations. Once all the models were created, they were placed into one block called a subsystem or module. Images can be added to the module blocks to represent the systems. The developed virtual lab consists of 8 modules as shown in Figure 3.

Next, a mask is created for each module. The mask allows for images to be displayed on the block by opening the Mask Editor and using the MATLAB *image()* function that is typed into the Icons and Ports tab in the Icon drawing commands panel. The images and the GUI are saved in the same folder. The mask also enables a user interface to pop up when the block is double-clicked. The user interface is created in the Mask Editor under the Parameters & Dialog Tab. The user interface is created using the parameter. The dialog tab is where we can create tabs, user inputs, sliders, and others along with their respective variables that are embedded into the Simulink and Simscape blocks.

Figure 3. MATLAB Simscape GUI program and its submodules.

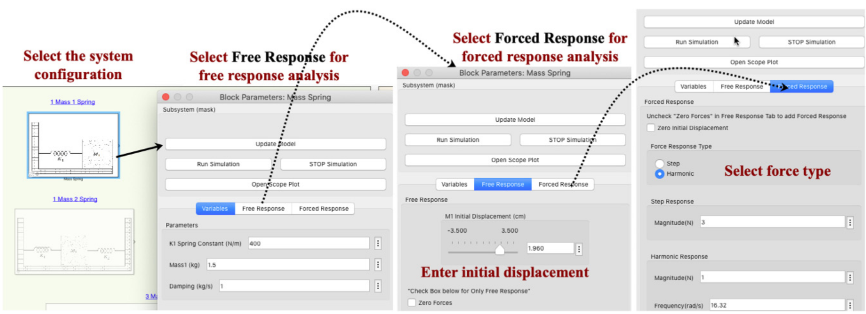

Figure 4. MATLAB Simscape GUI program user interface.

Figure 4 depicts the user interface. First, a module is selected (such as a mass and spring system) and double-clicked to enter the parameters of the system and enable study of either free or forced response by selecting the appropriate buttons in order. Once the simulation is run, the output data collected during the simulation will be exported to the workspace for further analysis.

Case studies and implementation of the GUI program in mechanical vibrations and control theory courses

The developed Matlab Simscape GUI program can be utilized to study and perform analysis in an introductory level machine dynamics and vibrations and control theory courses and their associated laboratories. This section briefly presents the case studies and how our developed MATLAB App can be implemented to visualize the concepts and assign them as a class activity or homework assignment.

Case study I: vibration isolation design

When mechanical engineers design a machine or a mechanism, vibrations that are caused by either external sources or the clearances in the joints are undesired and need to be reduced or eliminated if possible. Vibration control can be achieved by a passive design or by an active controller with the addition of electronics. One cost-effective solution for a vibratory system subjected to harmonic motion is the design of a secondary system comprised of a sliding mass and spring as illustrated in Figure 5.

Potential learning outcomes that can be achieved by studying a system of this type can be enumerated as:

- Design a SDOF system using Matlab Simscape GUI program,
- Derive the equation of motion of a SDOF system,
- Obtain system response data from a Matlab GUI program,
- Obtain the natural frequency using two methods (equation of motion and simulated response),
- Design a vibration isolator for a system having base excitation,
- Describe how the reduction in amplitude is affected by the choice of different vibration isolator mass and spring constants,
- Visualize the forced response of SDOF and 2 DOF mechanical systems.

All of these learning outcomes are incorporated in the learning activity we designed. First, students were asked to design a SDOF system by selecting the correct title in the GUI program and changing the mass, spring and, damping constant values accordingly as illustrated in Figure 6. Next, they derive the equations of motion either using Lagrange theorem or Euler's laws of motion as

$$m\ddot{x}(t) + kx(t) = F_0\cos(wt) \tag{1}$$

and find the natural frequency of the system. As a case study, m_1 and k_1 are selected to be 2 kg and 400 N/m, and also the damping constant of 1 Ns/m is introduced in the GUI program to eliminate large displacements falling outside the workspace.

Once the students run the simulation by introducing an initial displacement, they should also be able to calculate the period, frequency in Hz, and natural frequency from the free-response as shown in Figure 7(a). This would allow them to better understand that the damping does not affect the frequency of oscillations. Reading the first two consecutive peak values and their corresponding time values from the graph, the logarithmic decrement ($\delta = \ln\left(\frac{A_1}{A_2}\right)$, A_i being the amplitude of oscillations), damping ratio (ζ), damped frequency, natural frequency, and damping constant are calculated as 0.1384, 0.022, 13.65 rad/sec, 13.66 rad/sec, and 1.2 Ns/m. The slight difference between the

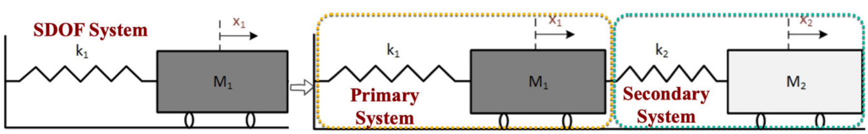

Figure 5. Passive vibration isolator design.

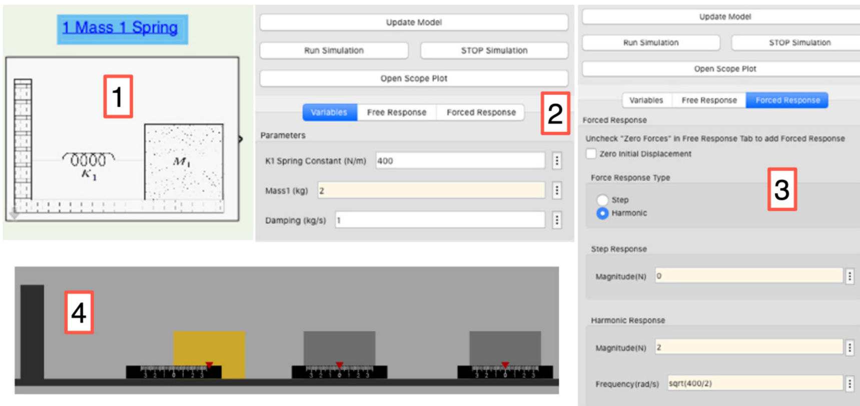

Figure 6. Free response of SDOF system using MATLABatlab Simscape GUI program.

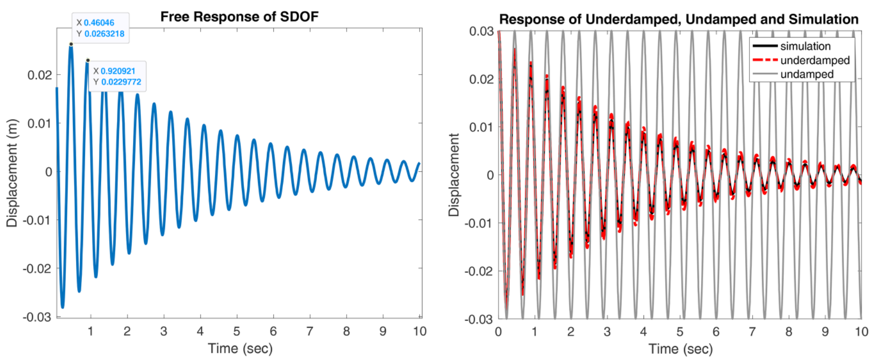

Figure 7. Free response of SDOF system: (a) free response of the primary cart and (b) theoretical and simulation response of the primary cart system.

actual and calculated damping constant might be due to the maximum readings from the graph and the internal friction between the components of the Simscape Model. The responses of the undamped and underdamped system are

$$x_{undamped}(t) = x_0 \cos\left(\omega_n t\right) + \frac{\dot{x}_0}{\omega_n} \sin(\omega_n t) \tag{2}$$

$$x_{underdapmed}(t) = e^{-\zeta\omega_n t}\left[x_0 \cos(\omega_d t) + \frac{\dot{x}_0}{\omega_d} \sin(\omega_d t)\right] \tag{3}$$

where x, $\dot{x}$, and x_0 are the position, initial velocity, and initial position of the cart. Both the theoretical solutions and simulation responses are plotted in Figure 7(b).

Next, students select the forced response data and apply a force in the form of $f(t) = F_0\cos(wt)$, where F_0 is the amplitude of the force and w is the forcing frequency which is selected to be the natural frequency of the system. Students record the maximum displacement.

Finally, the students are asked to design a vibration isolator to reduce the oscillations on the primary cart when the primary system is excited at its own natural frequency. For a second-order system depicted in Figure 5, the displacements of the carts are expressed as

$$x_1(t) = \frac{F_0(k_2 - m_2w^2)}{(k_1 + k_2 - m_1w^2)(k_2 - m_2w^2) - k_2^2} \tag{4}$$

$$x_2(t) = \frac{Fk_2}{(k_1 + k_2 - m_1w^2)(k_2 - m_2w^2) - k_2^2} \tag{5}$$

where x_i is the displacement of the cart *i,* and $k_1,\ k_2$ are the spring constants of the springs connected to mass 1 (m_1) and mass 2 (m_2). Since the goal is to dampen the oscillations acting on the primary cart, to make $x_1(t) = 0$ or as small as possible the below equation should be satisfied

$$\frac{k_1}{m_1} = \frac{k_2}{m_2} \tag{6}$$

Once the students design the secondary system, they will be able to observe the motion behavior of both carts and plot the response of the primary cart to find the maximum displacement. This allows them to calculate how much the oscillations were damped with the addition of the secondary system. For the given example, steady-state displacements of the primary cart on SDOF and 2 DOF systems when a force of $F(t) = 2\cos(\omega_n t)$ is applied are found to be 0.1082 m and 0.005884 m, yielding 94.5% amplitude reduction as shown in Figure 8.

Determining the natural frequencies and mode shapes of a 2 DOF system

The objectives of this class or laboratory activity are:

- Determine the two natural frequencies of a 2 DOF system
- Visualize the mode shapes of a 2 DOF system
- Investigate the effect of the initial displacement on the free vibration of a 2 DOF system
- Use a Matlab Simscape GUI program to create SDOF and 2 DOF systems

Theory: Consider a 2 DOF rectilinear system consisting of two masses and three springs as illustrated in Figure 9. Since each cart is limited to displacement along the horizontal

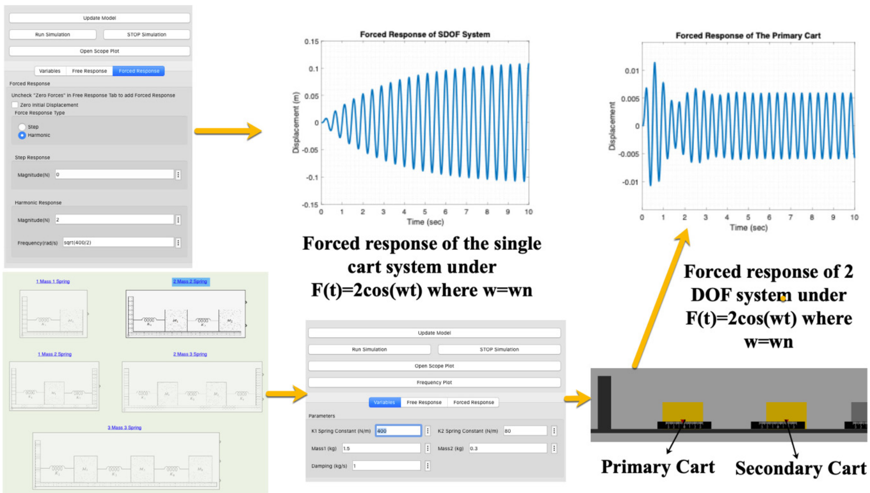

Figure 8. Simulation of vibration isolator design.

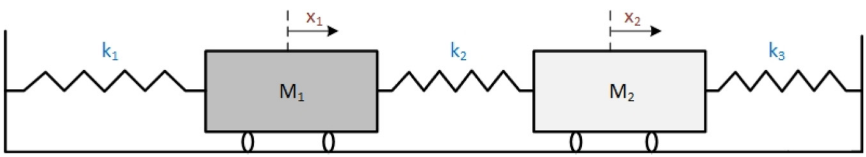

Figure 9. The sketch of a 2 DOF system consists of two carts and 3 springs.

axis and we are only interested in the calculations of the natural frequencies, a lumped mass-matrix model can be applied and is obtained as

$$\begin{bmatrix} m_1 & 0 \\ 0 & m_2 \end{bmatrix}\begin{bmatrix} \ddot{x}_1(t) \\ \ddot{x}_2(t) \end{bmatrix} + \begin{bmatrix} k_1+k_2 & -k_2 \\ -k_2 & k_2+k_3 \end{bmatrix}\begin{bmatrix} x_1(t) \\ x_2(t) \end{bmatrix} = \begin{bmatrix} 0 \\ 0 \end{bmatrix} \tag{7}$$

Assuming each mass is oscillating in the form of $x_i(t) = A_i\cos(\omega t - \phi)$, with i, w and ϕ being the cart number, frequency of oscillations and phase difference, Eq. 7 yields

$$\begin{bmatrix} k_1+k_2-m_1\omega^2 & -k_2 \\ -k_2 & k_2+k_3-m_2\omega^2 \end{bmatrix}\begin{bmatrix} X_1 \\ X_2 \end{bmatrix}\cos(\omega t - \phi) = \begin{bmatrix} 0 \\ 0 \end{bmatrix} \tag{8}$$

So, the natural frequencies of the 2 DOF system can be calculated as

$$\omega_{1,2} = \frac{\sqrt{k_1m_2 + k_2m_1 + k_2m_2 + k_3m_1 \pm \sqrt{\begin{matrix} k_1^2m_2^2 - 2k_1k_2m_1m_2 + 2k_1k_2m_2^2 - 2k_1k_3m_1m_2 + k_2^2m_1^2 + \\ 2k_2^2m_1m_2 + k_2^2m_2^2 + 2k_2k_3m_1^2 - 2k_2k_3m_1m_2 + k_3m_1^2 \end{matrix}}}}{2m_1m_2} \tag{9}$$

Example: For ease of illustration, an example system is designed by choosing $m_1 = m_2 = 1.34\ kg,\ k_1 = 400\ N/m,\ k_2 = 200\ N/m\ and\ k_3 = 400N/m.$ Then, the two natural frequencies of the system are 17.27 rad/sec (≈2.74 Hz) and 24.43 rad/sec (≈3.88 Hz). The natural frequencies are substituted in Eq. 8 in order to calculate the mode ratios of the system. The mode ratios are found as

$$\omega = \omega_1 = 17.27 rad/sec, \quad Mode\ Ratio\ 1 = \frac{A_1}{A_2} = 1 \tag{10}$$

$$\omega = \omega_2 = 24.43\ rad/\mathrm{sec}, \quad Mode\ Ratio\ 2 = \frac{A_1}{A_2} = -1 \tag{11}$$

The calculated mode ratios reveal that if the two carts are displaced in the same direction at the same amount, then both carts should be oscillating at 17.27 rad/sec (≈2.74 Hz). Similarly, if the carts are displaced the same amount but in opposite directions, the frequency of oscillations of both carts should be 24.43 rad/sec (≈3.88 Hz). If the carts are initially displaced randomly, then each cart should oscillate at its own natural frequency.

Within the Matlab Simscape GUI Simulations, students are first asked to design their own 2 DOF system in the GUI program. Following Eqns. 7–11, they obtain the natural frequencies and the mode ratios. Then, they enter the values on the GUI program following the same steps shown in Figure 10. The GUI program also allows the user to plot the power spectrum so that students can easily read the natural frequency of a MDOF system.

For the first case (mode ratio 1), the carts are displaced 3 cm to the right. Then, the second cart is displaced to −3 cm so that the amplitude ratio becomes (−1), satisfying mode ratio 2. Finally, the carts are displaced arbitrarily ($x_{10} = 3cm\ and\ x_{20} = -1\ cm$). The simulation results are shown in Figure 11. With the GUI program students are not only able to plot the displacement of the carts but also see how the carts move using the mechanics explorer. Based on our experience, the instructor can demonstrate the theory, after instruction on the concepts, within 5 min. Then, this activity can be given as a laboratory task for vibrations and control theory laboratories.

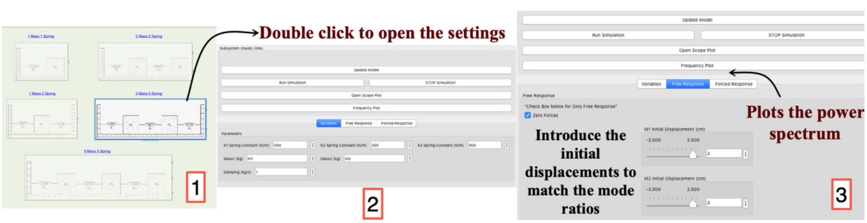

Figure 10. MATLAB GUI settings for the mode ratios.

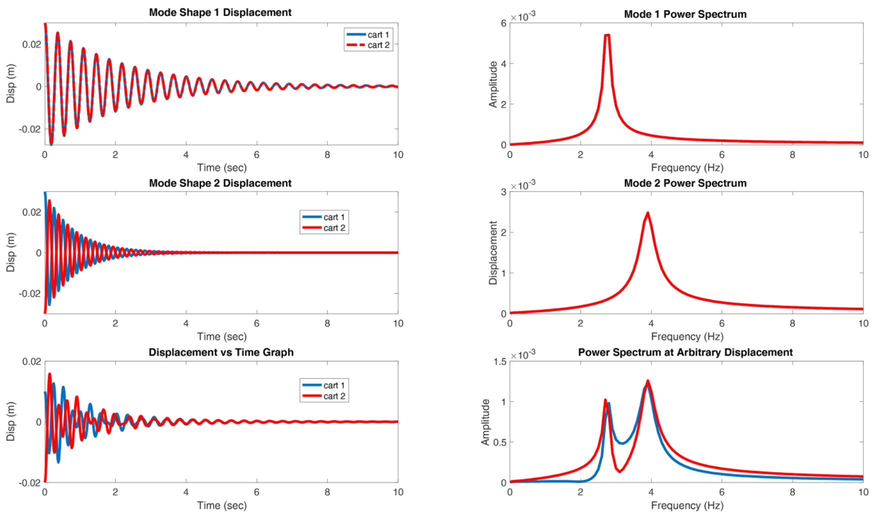

Figure 11. MATLAB Simscape GUI simulation response for the displacements and the power spectrum of the carts for mode shape 1, mode shape 2, and arbitrary initial displacements.

Trajectory control of a SDOF system

Undergraduate mechanical engineering students typically take introductory-level control theory as a senior and learn the fundamentals of control theory topics. Control theory covers several abstract concepts such as modeling of mechanical/electrical/thermal systems, block diagram reduction, transfer functions, state-space forms, stability, steady-state errors, root locus, and the proportional-integral-derivative (PID) control design. Although computer simulations significantly enhance student understanding, due to limited time instructors teaching the course often choose to leave out computer simulations. In many institutions, the control laboratory course is offered the following semester and the course is a pre-requisite for the laboratory. However, the activity offered here can be incorporated into a lecture course to address the concepts and pair them with the observation of physical behavior in a simple way for the student.

The learning objective of this activity is the design of a PID controller of a SDOF system using trial and error and Ziegler-Nichol's method so that the cart follows a well-defined trajectory. This activity demonstrates some key concepts associated with proportional plus derivative (PD) control, and subsequently illustrates the effects of adding integral action (PID) to minimize the error between the reference and the actual output. The traditional PID controller design finds broad application in industry such as machine tools, automobiles (cruise control), and spacecraft (attitude and gimbal control).

One of the main objectives of a PID controller design is to follow any desired trajectory. For a forced SDOF system, the equation of motion of the system is

$$m\ddot{x}(t) + c\dot{x}(t) + kx(t) = F(t) \tag{12}$$

The PID control equation is

$$u(t) = K_P(x_d(t) - x(t)) + \frac{1}{K_I}\int(x_d(t) - x(t)) + K_D\frac{d(x_d(t) - x(t))}{dt}$$
$$= K_P e(t) + \frac{1}{K_I}\int e(t) + K_D\frac{de(t)}{dt} \tag{13}$$

Here *u(t)* is the control function, x_d, $\dot{x}_d(t)$, $\ddot{x}_d\,(t)$ are the desired trajectory, velocity, and acceleration, K_P , K_I, K_D are the proportional, velocity, and derivative control coefficients. The control coefficients can be tuned either using Ziegler Nichols, pole placement, or the trial-and-error method.

Although a complex dwell motion is selected as a reference trajectory here, the user can define any trajectory using the Matlab user-defined function or different types of signals using the Simulink Library source signal blocks such as step, ramp, or sinusoidal signal. The dwell signal is generated using the *dsigmf* function in MATLAB. The function calculates the differences between two sigmoid functions such that

$$f(x;\, a;\, c) = \frac{1}{1 + e^{-a(x-c)}} \tag{14}$$

where x is the input, and a and c are the parameters of each sigmoid function.[12] The reference trajectory is created as the combination of several dwell functions. The user can change the settings of the sigmoid function for the desired dwell trajectory. In this case study, an example trajectory is created by selecting the gains at 3 cm, 4 cm, and 2 cm using the time delay blocks as shown in Figure 12. The gains can be changed to any desired value as they indicate the reference displacement of the carts.

Students first select the Mass-Spring PID controller subsystem, then they enter the parameters of the SDOF system they are working on, and finally they select the PID controller to change the controller coefficients. These steps are illustrated in Figure 13.

Trial and Error Method. Students are asked to adjust the optimal controller constants using the trial-and-error method until the SDOF system follows their reference trajectory. For the case study the mass, spring, and damper constants are selected as 2 kg, 400 N/m, and 1 Ns/m. The system response for different choices of the PID controller is shown in Figure 14.

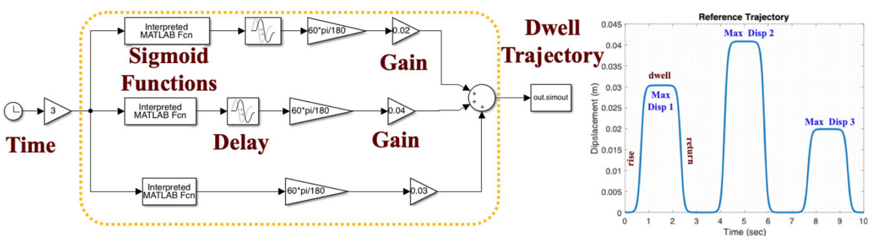

Figure 12. Simulink model and plot of the reference trajectory using dsigmf function.

Ziegler Nichols Method. Ziegler-Nichols provides a method to determine the PID controller coefficients. Once the proportional (or in other words the gain control) constant that causes the system to undergo infinite oscillations is noted, the period of oscillation, P_{cr}, is read from the simulation response. Ziegler-Nichols method suggests the PI controller constants as $K_p = 1.45K, \quad Ki = 1.2K / P_{cr}$. For the case study here, the period of oscillations and the gain constant are found to be 0.04 s and 835 so that the PI controller coefficients yield $K_P = 375$ and $K_i = 1000$ as the simulation responses and error. These results are shown in Figure 15.

Survey results for student perceptions of learning for the free and forced response studies

The Student Assessment of Learning Gains survey, or SALG,[14] was adapted for use as a means of an indirect assessment of student learning based on the designed activities for the free and forced response. This learning activity carried a grade worth 10% of the overall grade for the course. The evaluation was based on students' in-class performance, accurate completion of the tasks in the laboratory handout, and the quality of the submitted report.

In order to collect honest and accurate feedback from the students, the SALG survey was employed online several days after the due date of the lab activity report and results were not shared with the instructor until after final course grades were submitted. The class enrolled 107 students and produced 17 usable responses. The version of the SALG used for this study contained questions addressing several important areas:

- Lab materials and process impact on overall learning (lab handout instructions, learning objectives for the lab, interactive nature of the simulation (visualizations, graphs, changing parameters, etc.), asynchronous nature of the lab (working at your own pace), individual support as a learner from your instructor)
- Lab write-up impact on learning (mental stretch required, grading system used, feedback received)

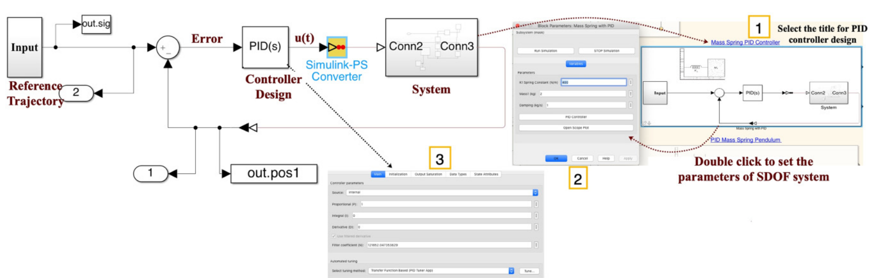

Figure 13. Setting up the PID control of SDOF system subsystem.

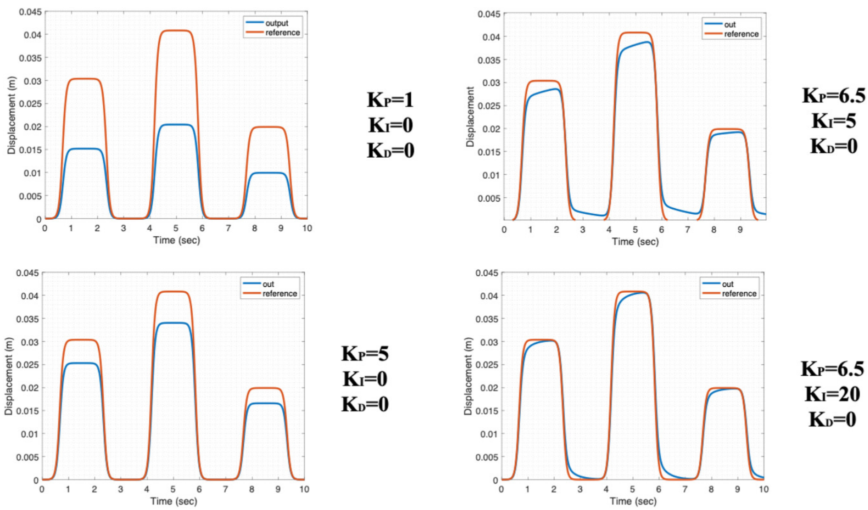

Figure 14. The controlled system responses for various PID controller designs using trial and error method.

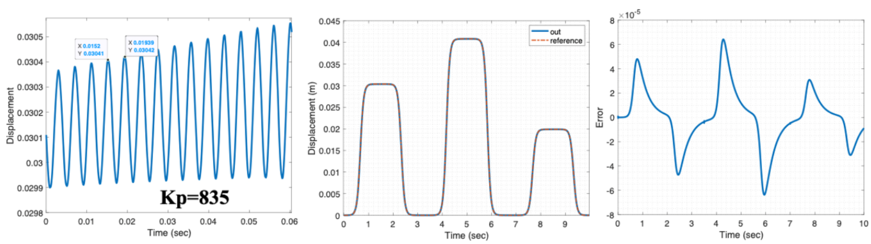

Figure 15. The controlled system responses for various PID controller design using Ziegler-nichols method.

- Lab impact on engineering skills (following technical instructions, data collection from the Matlab Simscape model, breaking down and analyzing problems, solving problems, connecting theoretical concepts to real physical systems, designing a system to meet certain specifications)
- Lab impact on learning gains (understanding fundamental theory/concepts underlying the lab, recognizing the relevance of this lab to real-world issues, ability to think through a problem involving vibrations and control, confidence in your ability to conduct this type of learning activity on your own at home)
- Comparison of Simscape lab models to videos (advantages and disadvantages of each, improvements that could be made to each)

Results from the SALG survey on all questions indicated the learning activity was of significant help (4 or 5 on a 5-point scale) for the large majority of students.

First, as shown in Figure 16, the students clearly felt that the lab materials (instructions and learning objectives) were helpful for their learning. While a few students felt the learning objectives were of only a little or moderate help, all students rated the lab instructions as providing much help or very much help for their learning with about 65% saying the lab handout was very much help. However, the value of this lab activity in supporting student learning was reported more strongly on items related to the lab process (interactivity, asynchronous nature, instructor support). In particular, 100% of students felt that the interactive nature of the simulation was either much help or very much help for their learning, with over 80% rating it as very much help. It is precisely this interactive nature of simulations that have been shown to improve student understanding in other contexts, such as the PhET simulations developed at the University of Colorado.[15]

The lab write-up process was viewed as helpful to learning by students as well. While the mental stretch required was viewed as less helpful than the grading scheme and instructor feedback, all were viewed as providing much help or very much help for student learning, as shown in Figure 17.

Students also reported significant perceived learning gains in developing engineering skills because of completing the learning activity for this simulation. Results are shown in Figure 18. In all but one skill over 90% of respondents reported their engineering skills increased either a lot or a great deal. The highest-rated skills gains were in designing a system to meet certain specifications and in data collection within the Matlab Simscape model. Following technical instructions were rated slightly lower, with over

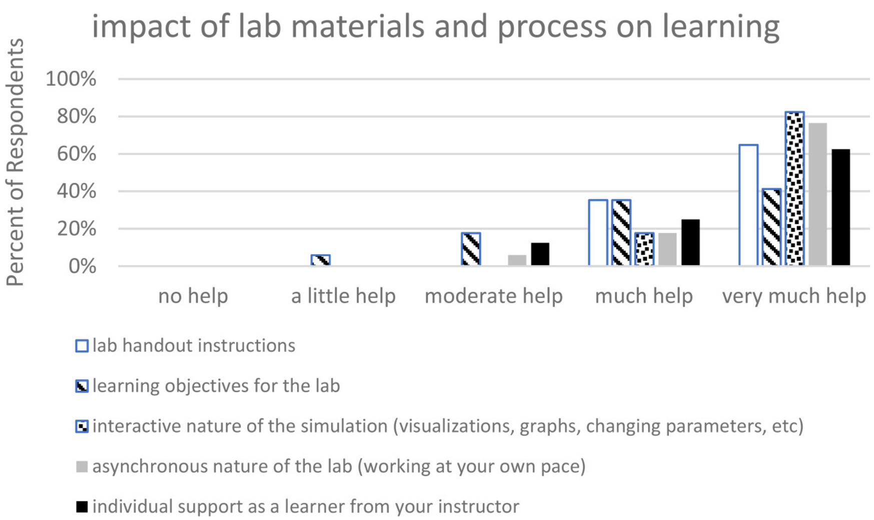

Figure 16. Student response to impact of lab materials and process on learning.

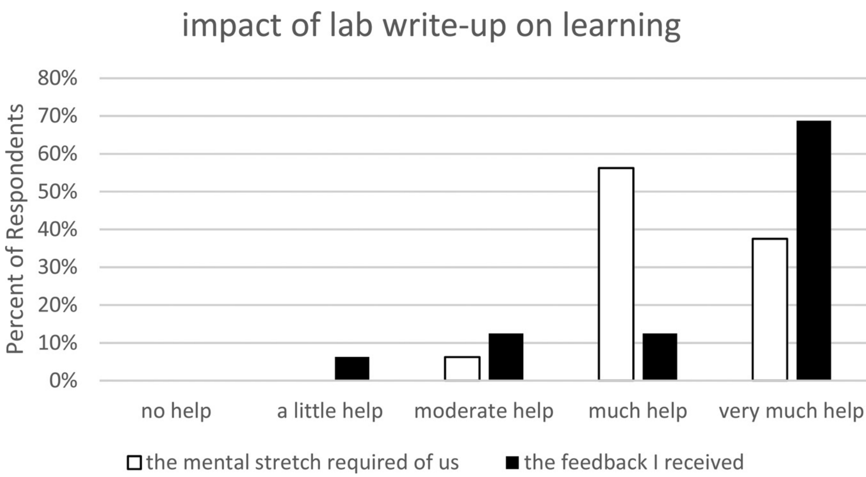

Figure 17. Student response to impact of lab write-up on learning.

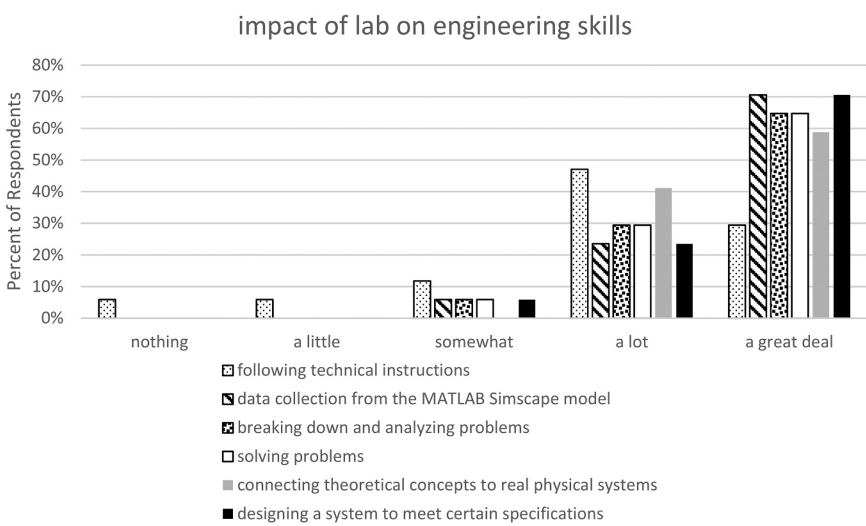

Figure 18. Student response to gains in engineering skills.

20% of students reporting gains of none, a little, or somewhat. However, building this skill was not a specific goal of the activity.

Finally, students reported on their general learning gains from completing the learning activity for this simulation as summarized in Figure 19. While students reported strong gains in all the items for general learning gains, they reported the strongest gains in their ability to think through a problem involving vibrations and control. This was

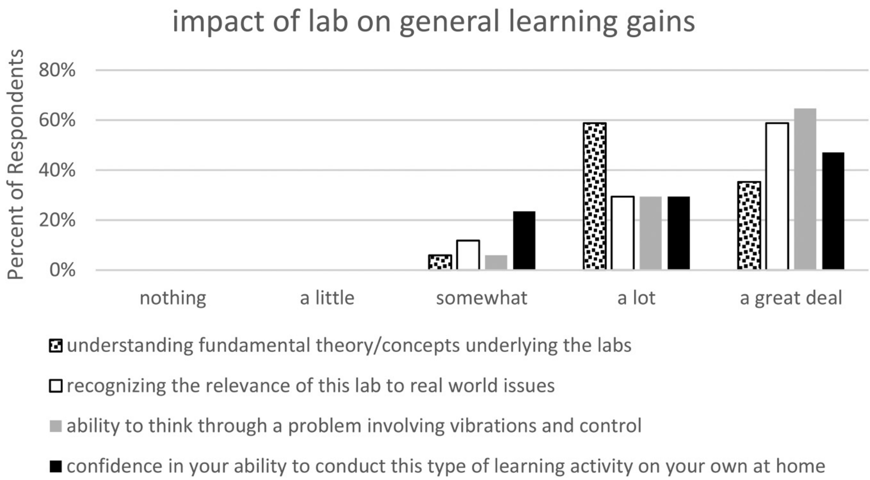

Figure 19. Student response to general learning gains.

followed by recognizing the relevance of this lab to real-world issues as the second strongest reported gain. Students reported slightly lower gains for understanding fundamental theory/concepts underlying the labs. This was due to fewer students reporting "a great deal" of gains in this area even though only 1 student reported gains less than "a lot". The lowest rated general learning gain was in student confidence in their ability to conduct this type of learning activity on their own, with nearly 25% of students reporting the lab having only "somewhat" of an impact in this area.

Student comments about their learning from the simulation were nearly universally positive. In particular, several themes were prevalent in the comments: students appreciated the clarity of instructions and expectations, students found the necessity to interact with the simulation by manipulating data valuable, and students saw value in the visual representation of the system behavior. However, some students did struggle with using the software on their computer and cited issues with their ability to access or set certain features needed to successfully run the simulation. A few representative comments are included below:

- "The videos are super helpful in understanding what we're doing"
- "Items like the systemIdentification function … [were] extremely useful to me. I [was] able to take a lot of what I learned about Matlab in this class and apply it in my senior design project. Maybe even more so than the intro to Matlab class I took"
- "Using this method helped visually see a system and all of its components"
- "I enjoyed the visuals provided by the Simscape models"
- "Sometimes I wouldn't have access to certain functions as the version of MATLAB I used did not grant access to it"

Conclusions

The introduction of a MATLAB Simscape GUI program to simulate the behavior of modeling and control of dynamical systems for vibrations and control theory courses, and their associated laboratories, shows significant promise as a tool to enhance student learning in these courses. The program is versatile in that it can be applied to multiple scenarios applying to SDOF and 2 DOF systems. Here we have described learning activities for three key topics: vibration isolation design, determining the natural frequency and mode shapes in a 2 DOF system, and trajectory control in a SDOF system. This ability to use the program for multiple concepts provides a significant learning advantage as students become familiar with the program operation and are able to focus more on how theory applies to mechanical system behavior in vibrations and control applications. Further, student responses to the SALG survey indicate they found the learning activities designed to address the key topics above to be of much help or very much help in understanding the theoretical concepts and also in helping them develop their engineering skills.

Future work to extend this pilot effort by investigating student performance through a controlled experimental approach may be of value in demonstrating whether student perceptions of learning are supported with increased performance on homework or exam questions. Further, the extension of the MATLAB Simcsape GUI program capability to address additional key topics and important system behavior applications will be of value, as the program could be threaded through an entire course. The open-source nature of the program can be leveraged to facilitate these future research possibilities with different types of student populations.

Declaration of conflicting interests

The author(s) declared no potential conflicts of interest with respect to the research, authorship, and/or publication of this article.

Funding

The author(s) received no financial support for the research, authorship, and/or publication of this article.

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