Undergraduate Research Opportunity for a Virtual Vibrations Lab Generation

Patrick Bass and Robert Fenney
Department of Mechanical Engineering, The Citadel

Abstract

This report focuses on the development of a computer simulation that will be used in a mechanical engineering vibrations course. The incorporation vibrations topics into the curriculum is new at The Citadel and so a need to quickly develop meaningful laboratory experiences arose and offered a student-research opportunity. With the unpredictable nature of the COVID-19 pandemic, the aim for the vibrations laboratory was for it to be a virtual lab in case the students needed to quarantine for any reason. The simulation will focus on allowing the students to better understand how parameter adjustments can influence the behavior of undamped and damped systems. The creation of the simulation was presented as a challenge to a senior-level undergraduate student for development of the simulation in the fall semester for implementation in the following spring semester. A timeframe of two months was provided so that the simulation could be well vetted and integrated into the rest of the suite of laboratory sessions for the course. With the short completion timeframe, periodic update meetings, and evaluation proceedings, the framework of the project was aimed at providing an experience that would be similar to what the student would face if they were to take on contracted work in their career field. This report will document the learning opportunities and limitations of the project.

Keywords

Undergraduate research, simulation, control systems, vibration analysis

Introduction

Control systems is an interesting and challenging topic. Virtually all electronics and electromechanical devices use them in some capacity with whether that be the accelerometer and stopping system in automobile seatbelts, [1] industrial robots, [2] aircraft, [3] spacecraft, [4] air conditioning systems, [5] etc. Students however, find this topic to be difficult to grasp and so finding meaningful and appropriate laboratory exercises is key for translating the sometimes abstract topics into something that is physically and intuitively relatable. This report will develop the development of a simulator that accurately characterizes the vibrating behavior of a control system under external excitation as an undergraduate research project.

The undergraduate control systems sequence at The Citadel includes two courses. In the first course, taught in the fall, students learn about classical control, which encompasses topics like evaluating stability, steady-state error, and transient response for simple electrical, mechanical, and electromechanical systems. The course culminates in applying these lessons to root locus and frequency response design. The second course, taught in the spring, focuses on modern control theory, to include state space and digital control theory. In the past two years, work has been done to the curriculum of the second course to incorporate vibrations engineering into the course. This addition was conducted for two reasons: 1) the study of vibrations and how systems oscillate under an applied load, like the crosswind causing a harmonic oscillation in the Tacoma Narrows bridge and ultimately destroying it, [6] is a natural extension to the lessons on bode plots and their application to audio equipment; 2) questions on vibration topics are included in the Fundamentals of Engineering (FE) exam and this course was the logical choice for exposing the students to these subject areas.

The second course in the control systems sequence is also the course that comprises all of the laboratory exercises. There are currently five labs that have been developed for the course and they entail hands-on learning concerning topics like open-loop response, closed-loop response, and proportional-integrator-differentiator (PID) compensator design. Inclusion of vibrations into the control systems curriculum offers the opportunity to refresh the current lab sequence and to add in new labs to illuminate various vibrations areas. In the first offering of vibrations topics in the sequence, a sixth lab was added to incorporate vibrations topics. It was fairly simple and required students to enter in various parameters into a simulator and discuss the results. Though this notionally illustrated vibration responses for systems, the simulator [7] utilized some parameters not discussed in class and did not provide the clarity desired in its demonstration of vibration topics. Therefore, there was an opportunity to expand on the simulation's potential and more closely align the virtual lab to the course's learning objectives.

An additional benefit, and the focus of this report, is the incorporation of students in the development of this new laboratory exercise. This opportunity evolved into an undergraduate research project and allowed the students the ability to have buy in to the learning activities they would encounter in class. As such, this report comprises a work-in-progress study of the work completed by an undergraduate student in their pursuit to develop a new vibrations lab to be incorporated into the class. An outline of the research parameters will be provided and a synopsis of the student's experience will be detailed. Undergraduate research provides the opportunity for students to gain a deeper insight and understanding of a topic of interest. Additionally, it provides undergraduate students research experience, which students do not typically get until their senior year or if they pursue an advanced degree. [8] Developing this lab created the perfect opportunity for this student to expand their learning capabilities.

Research Goal and Parameters

As stated, this report comprises a work-in-progress study of the work completed to develop a virtual simulator for analyses of vibrating systems. The student had the fall semester to get a working simulator for use in the spring semester for when the labs are utilized. The simulator was to have the ability for students to vary parameters easily and to have the results show up on screen instantaneously so that they could immediately see the results of their changes. The to-be-developed laboratory problem statement would then task students to finding a specific response within the simulator and then replicate the results in external software, like Matlab. The virtual simulator allows for students to remotely complete the lab if external influences, like the COVID-19 pandemic, force learning in an online-only setup. Additionally, one of the learning objectives for the course is to "examine a damped physical system that utilizes a control system and determine its ability to meet performance specifications using Vibration Analysis techniques." This lab simulation will enable the students to practically internalize how to do this.

The starting functions to be analyzed were for systems that had undamped and damped oscillations. The governing equation for simple undamped harmonic oscillatory response is:

$$x(t) = A\cos(\omega t + \phi) \tag{1}$$

where, A is the amplitude of displacement, ω is the angular frequency, and ϕ is the phase angle of the displacement. In the second simulation, a damped simple harmonic oscillatory response was modeled and its corresponding equation is:

$$x(t) = Ae^{-\frac{bt}{2m}}\cos(\omega t + \phi) \tag{2}$$

where, the additional parameters b and m stands for the damping coefficient and the system mass, respectively.

Current Simulator Status and Success

The development of the vibrations simulator started with an initial expectations brainstorming session. **Figure 1** shows the initial desired user interface and output for the simulator. The bottom of the view graph shows rectangular slider bars for how the student will use the tool. Above that is the real-time output that the student will see update as they adjust the sliders. From this initial mock up, the student was asked to work through the required software development process to make it a viable tool for use in class.

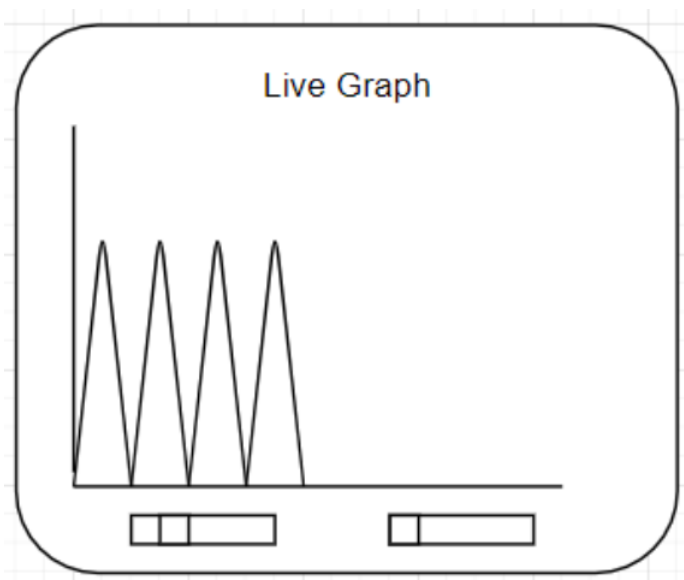

Figure 1: Desired vibrations simulator output and user interface

The student used a combination Python and its pertinent libraries and Jupyter notebook for generating live code and real-time visualizations for applied equations. Work was confined to single-degree-of-freedom systems for later expansion to multi-degree systems. As work progressed, the final representation of the simulator comprised two options for both the undamped and damped oscillatory systems. The first option comprises the slider bars as mentioned before. The implementation of this feature can be seen in **Figure 2a** with the mass and stiffness parameters governing the undamped response. These two parameters relate to **Equation 1 and 2** through the relationship $\omega = \sqrt{k/m}$. In **Figure 2b** another way to use the simulation is to insert and adjust the equation directly into the user interface window. The figure shows an oscillatory response for a system with a low stiffness.

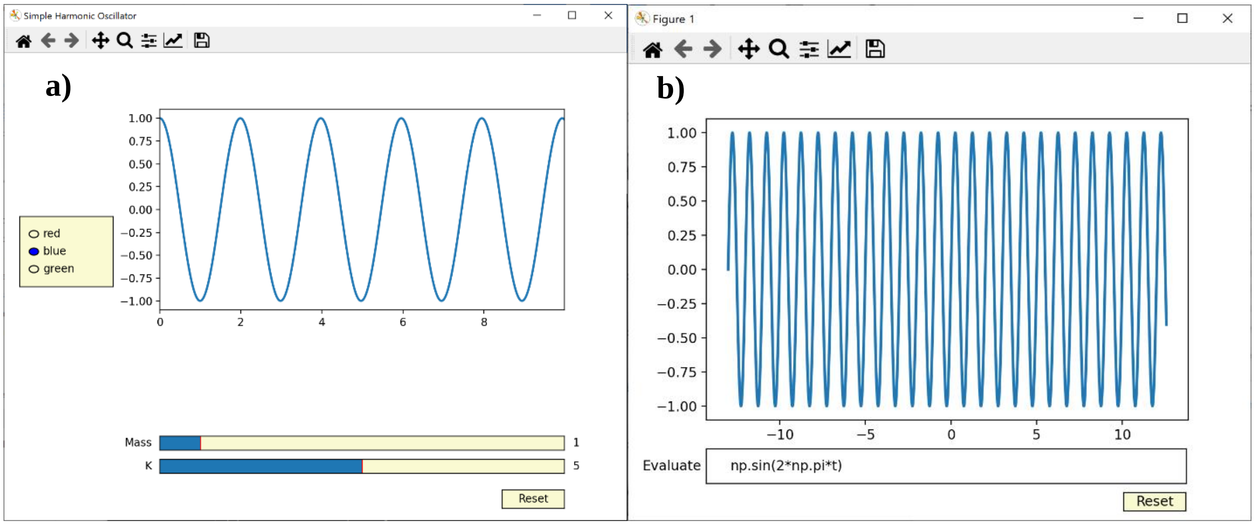

Figure 2: a) Slider and b) equation user input interfaces for undamped vibrating systems

The results of the simulator were extended to an under damped system where the vibrations damped out to a final value over time. The same two interfaces shown with the undamped system can be seen here with **Figure 3a** using sliders and **Figure 3b** using an equation for user inputs. The inherent flexibility in these results is clear and will provide for interesting laboratory exercises and objectives for future control systems students.

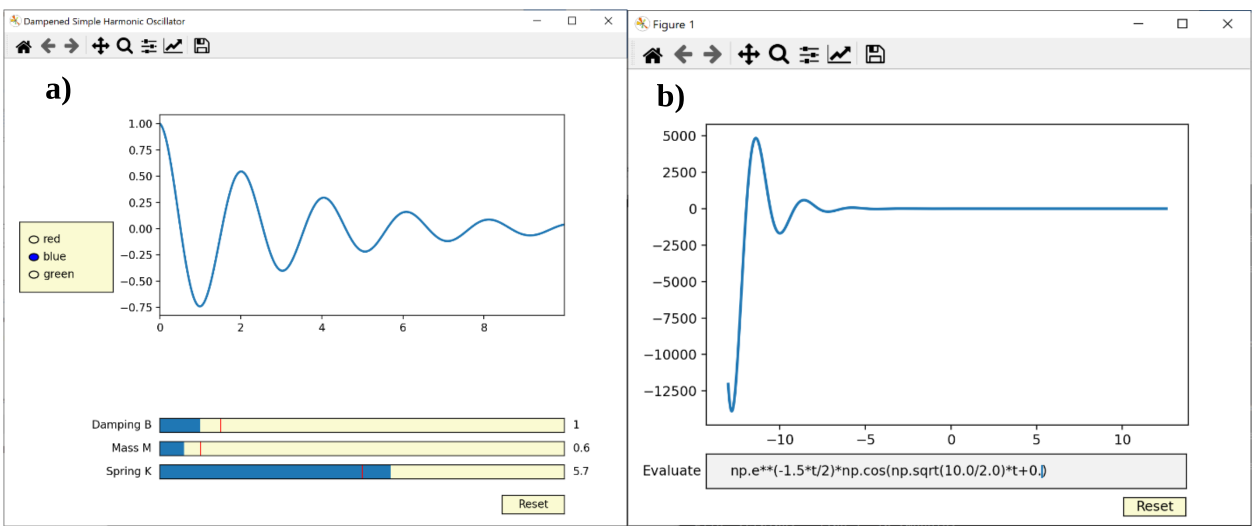

Figure 3:a) Slider and b) equation user input interfaces for under damped vibrating systems

Student Perspective

With regards to the design process, the undergraduate student was asked to provide their perspective on how to go from an initial idea to a final project and the inherent challenges that iterative process entailed. Below is the direct feedback from the student about the project. It has been a successful process throughout the fall and work will continue into the next semester.

> *"When I first began this research project, I was constructing simulations for vibrational systems. My results were to be presented in classroom settings for the Mechanical Engineering department. Because I have taken a Control Systems class and because I understood the underlying theory and mechanics, I expected the simulations to be easy. Although I felt confident in my knowledge, I did not anticipate the inherent difficulties that came with constructing the simulations. I chose to program in Python, using various open-source scientific packages, to minimize the upfront cost. Python is free, easy to learn, and is becoming increasingly more common in the scientific community. When designing the vibration simulations, however, I had to overcome various challenges. Most of the challenges were based around the limitations of the Python packages. I had to change my final designs for the programs to accommodate these limitations. By the end of this research project, I had a firm grasp of the iterative design process involved in the Python development environment. Paul Erdos, a 20th century mathematician, once said, "A problem worthy of attack, proves its worth by fighting back!" I would like to think that the many struggles and challenges I experienced during the design and implementation phase will mean my programs will prove useful to the Mechanical Engineering department in the future."*

Future Work

Initial implementation of the vibrations lab will use the code, as is, for set laboratory outcomes. Future work for this lab or for making an additional vibrations laboratory experience would be to extend the lab to a programming exercise where the students could be tasked with editing the code to incorporate another relationship to be simulated, such as a system with a rotating unbalance. They already have courses centered around learning Matlab, but this would expose them to other programming languages like Python. The main code to be used would be copied from the existing blocks for undamped and damped oscillations. The student would then redefine variables and edit the equation to be populated to the screen. Initial functions would look at those which varied with time and future functions could change the independent variable to frequency to mirror topics learned previously, to include bode plots. Bode plots are taught in the first semester of control systems and so extending the simulation to this area would provide a link in the curriculum.

Conclusion

This report comprised the work-in-progress results for an undergraduate research project involving developing a virtual vibrations laboratory exercise to meet the learning objectives for a control systems course. The development of this lab enabled the flexible implementation of 'hands-on' learning to allow for content delivery even when unforeseen circumstances, such as the COVID-19 pandemic, force quick transitions to all-online learning. Additionally, it was shown that the current functionality of the simulator allows for the students to either use slider bars to adjust individual parameters for a given relationship and that they can immediately view their effect. This allows laboratory exercises to target specific system performance and allow the students to tweak the sliders until they are met. The research project had the dual outcome where a functional simulator was developed for use in the vibrations course and it also enabled the undergraduate student the ability to extend the skills they learned in class to solve an open-ended problem and to work through how to learn on their own new skills necessary for the completion of the project. Future work will include finalizing the simulator, generating the classroom laboratory problem statement, and codifying the process for future updates and adaptations for other vibrations and control systems relationships.

References

[1] J. Tabe, "Smart seatbelt control system". USA Patent US6728616B1, 27 April 2004.

[2] L. Ziao, J. Gong and J. Chen, "Industrial Robot Control Systems: A Review," *Proceedings of the 11th International Conference on Modelling, Identification and Control,* pp. 1069-1082, 2020.

[3] N. Huynh, "Systems, apparatuses, and methods for moving aircraft control surfaces". USA Patent US7,059,563, 13 June 2006.

[4] A. J. Rohling, V. V. G. Neto, M. G. V. Ferreira, W. A. D. Sandos and E. Y. Nakagawa, "A reference architecture for satellite control systems," *Innovations in Systems and Software Engineering,* pp. 1-15, 2019.

[5] R. W. Haines and D. C. Hittle, Control systems for heating, ventilating, and air conditioning, Berlin: Springer Science and Buisness Media, 2006.

[6] K. Y. Billah and R. H. Scanlan, "Resonance, Tacoma Narrows bridge failure, and undergraduate physics textbooks," *American Journal of Physics,* vol. 59, no. 2, pp. 118-124, 1991.

[7] COEP Virtual Lab, "Spring Mass Damper System - Natural Vibration," College of Engineering, Dune, 2011. [Online]. Available: http://va-coep.vlabs.ac.in/NaturalVibrationSDOF/NaturalVibrationSDOF.html.

[8] P. Bass, N. Washuta, J. Howison, R. Gonzalez and C. Maier, "Benefits and Challenges of Undergraduate Research," *Proceedingsin the 2018 ASEE Southeastern Conference,* p. 10, 2018.

Dr. Patrick Bass

Patrick Bass is an assistant professor of Mechanical Engineering at The Citadel. He earned his Ph.D. in Materials Engineering from Auburn University. His main areas of research interest are electroactive polymers, space mechanics, and engineering education. He is also a major in the United States Air Force Reserve with a background in cyberspace operations and satellite communications.

Robert Fenney

Robert Fenney is a senior undergraduate student at The Citadel where he is majoring in Computer Science with a minor in Mechanical Engineering. His research interests include software development and translating this to applications in mechatronics.