Implementation of Virtual Labs on Fundamental Mechanical Vibrations Course

Dr. Carmen Maria Muller-Karger, Florida International University

Associate Teaching Professor and Associate Chair at the Mechanical Engineering Department at Florida International University. Full professor at Simon Bolivar University, Venezuela from 2002 to 2016. With a Bachelor's degree in Mechanical Engineering, a M.Sc. in Mechanical Engineering in the area of Rotodynamics from the University of Virginia, and a Ph.D. in Engineering Science in the area of Biomechanics from the Central University of Venezuela. Main interest in Simulation in Mechanical Engineering, Biomechanics, Motion Analysis, Finite Element Analysis, Mechanical Medical Devices Design, Mechanical Vibrations. Highly interested in Higher Education Curriculum Design, Academic Leadership, and teaching and classroom innovation. Courses taught: Intro to Engineering, Statics, Dynamics, Mechanics of Materials, Mechanical Vibrations, Intro to CAD (SolidWorks), Senior Design Project, Numerical Methods, Intro to Biomechanics.

Christopher Joa Chi Lang, The University of Texas at San Antonio

Christopher Joa Chi Lang graduated from Florida International University with a Bachelor's degree in Mechanical Engineering from the FIU College of Engineering and Computing. He is currently pursuing a Ph.D. in Mechanical Engineering at The University of Texas at San Antonio. His academic interests are centered on advanced engineering analysis, computational modeling, and the development of research methods that support innovation in mechanical engineering.

Dr. Luis Ulises Medina Uzcategui, Universidad Austral de Chile

Dr. Medina, a Doctor in Engineering holder, currently serves as an academic at the University of Austral de Chile (UACh), specializing in instrumentation, measurement, and mechanical systems dynamics. He is also the coordinator of the Innovation, Entrepreneurship, and Technology Transfer office at UACh. Previously, he held various academic-administrative roles at the Universidad Simón Bolívar (USB) in Venezuela, earning recognition for teaching excellence. With over 10 years of experience as the academic supervisor of the ASME-USB student group, affiliated with the American Society of Mechanical Engineers, he spent a sabbatical year as a Visiting Fellow at the University of New South Wales, Australia. Dr. Medina's applied research focuses on mechanical systems identification, vibration control, and metrology. His expertise extends to providing technical consultancy in vibration analysis for machinery and calibration of industrial transducers used in oil extraction. He has also facilitated professional development courses in mechanical vibration analysis, metrology, and quality control for industrial processes.

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Abstract —

Understanding fundamental concepts in Mechanical Vibrations is challenging for many undergraduate engineering students due to the high mathematical rigor, which often hinders their ability to connect theory with physical phenomena. Interactive virtual labs offer a promising approach to bridging this gap by providing accessible and engaging learning environments. This study focuses on the classroom implementation and usability assessment of the Virtual Mechanical Vibrations Labs (VMVLabs), a suite of simulations designed to support instruction on one-degree-of-freedom vibration systems. The labs were integrated into a 62-student undergraduate Mechanical Vibrations course and used to explore free, harmonically forced, and step-force responses. Usability and student perceptions were evaluated using a System Usability Scale (SUS) Survey, along with course reports, exam performance, and qualitative feedback. Results indicate high student satisfaction, strong usability ratings, and improved conceptual understanding of damping, resonance, and transient versus steady-state behavior. These findings suggest that virtual labs are an effective and scalable supplement to traditional instruction in Mechanical Vibrations.

I. Introduction

According to the Accreditation Board for Engineering and Technology (ABET) [1], engineering graduates must demonstrate the ability to integrate theory with practice by designing experiments, analyzing data, and acquiring new knowledge through appropriate learning strategies. Yet, ABET does not prescribe a specific number of laboratory courses to meet this requirement. A review of 120 course catalogs found that 50.4% of Electrical Engineering (EE) courses included physical laboratories, compared to 39.1% in Mechanical Engineering (ME) [2]. These findings highlight the value engineering programs place on laboratory-based courses, but also depict the challenges for disciplines such as ME, where laboratories often require greater investment in equipment, faculty labor, and physical space.

One area where these challenges are especially evident is in Mechanical Vibrations, a course that involves solving complex differential equations, analyzing dynamic systems, and interpreting abstract physical phenomena in the frequency and time domains. Students must integrate knowledge from previous courses in calculus, differential equations, linear algebra, and physics to model and analyze real-world vibration problems. Without a solid mathematical foundation, it becomes difficult to grasp key concepts such as natural frequencies, mode shapes, damping, and resonance, making the learning curve for this course particularly steep.

When in-person labs are not available, a virtual lab can help overcome the challenges of Mechanical Vibrations by providing an interactive environment where students can visualize and experiment with concepts that are otherwise abstract and mathematically intensive. Rather than only working through equations on paper, students can manipulate parameters such as mass, stiffness, and damping in real time, which helps bridge the gap between the mathematical model and the physical response and reinforces understanding. In this context, virtual laboratories are best viewed as a flexible resource that can supplement traditional instruction in settings where hands-on experiments already exist and serve as an alternative laboratory experience when physical infrastructure is limited, aligning with ABET expectations for integrating theory with experimental practice without prescribing a specific number or format of labs. To contextualize the development of such tools, a literature review of existing remote and virtual laboratories was conducted to identify current capabilities, typical roles of virtual experiments in the curriculum, and opportunities for improvement.

The authors developed the Virtual Mechanical Vibrations Lab (VMVLabs) presented in this paper. They are a standalone, offline educational application developed to support instruction in the Mechanics of Vibrations course by addressing the lack of hands-on experimental experiences commonly encountered in classroom settings. The tool simulates two primary systems: a single-degree-of-freedom (1-DoF) system consisting of an articulated rigid beam with an end mass connected to two springs, and for future applications a two-degree-of-freedom (2-DoF) system featuring a similar setup along with a vibration absorber composed of a secondary mass suspended by a spring. On the one hand, this tool will enable students to visualize vibrational phenomena caused by free vibrations and forced vibrations, thereby promoting a deeper understanding of fundamental concepts such as natural frequency, damped frequency, forcing frequency, resonance, critical frequency, magnification factor, and phase shifts, and the concept of vibration control using a tuned mass damper. VMVLabs are also intended to encourage students to use tools such as Excel and MATLAB to process, analyze, and interpret data from vibrational responses.

II. Literature review on virtual labs in Mechanical Vibrations

One example of a large-scale virtual laboratory initiative is the Virtual Labs project, initiated by the Ministry of Education, Government of India under the National Mission on Education through Information and Communication Technology (NMEICT). This program has expanded rapidly as a nationally coordinated effort to provide remote access to laboratory experiences in science and engineering, offering an accessible alternative to in-person laboratories for a wide range of institutions. Requiring only an internet connection, these tools are available online [3] and include a dedicated set for the Mechanics of Vibrations course. The modules cover free vibrations, forced vibrations, and vibration absorbers, allowing students to adjust system parameters, characterize systems, and observe the effect of damping on vibratory response. The labs implement 2D simulations of rigid and flexible systems with user-adjustable parameters, but they do not fully emulate hands-on laboratory experience: they emphasize steady-state response, provide limited options for data export and post-processing, and make it difficult to tie mathematical models to their physical realizations—gaps that deviates from the relevant ABET learning outcomes.

Tekes et al. [4] developed the Translational and Rotational Vibrations Virtual Lab using MATLAB Simscape, featuring primarily 2D and some 3D visualizations. The platform covers systems ranging from 1-DoF to 3-DoF, as well as more complex configurations such as a cantilever beam with an end mass and springs, a translational rotating umbalance system, pendulums, and basic translational models [4], [5]. Besides these tools, supplementary handouts were provided, giving theoretical background and an introduction to MATLAB [4]. A modified Student Assessment of Learning Gains (SALG) survey of 128 students reported mean scores of 4.86/6 for understanding theoretical concepts and 5.13/6 for connecting theory to real life. In the cognitive domain, students rated problem-solving skills at 4.77/6 and problem-decomposition skills at 4.73/6 [6]. On the one hand, MATLAB is used as the development environment because many institutions already provide access to it and often require students to take introductory courses in this software [5]; however, reliance on paid licenses can limit availability at some institutions. Simscape offers pre-built libraries for rigid and flexible systems and supports CAD model import for added complexity [5], but modifying configurations often requires the modification of Simscape blocks, which can pose challenges for both students and faculty members.

Medina, Muller, and Casanova [7] developed the Virtual Rotor Kit (VRK), an application built in PyChrono—a Python library based on the Chrono multi-physics simulation engine. The primary objective of this virtual lab was to facilitate understanding of the Influence Coefficient Method for rotor balancing under harmonic-periodic excitation. The VRK was evaluated as an educational tool at Florida International University (33 students) and Universidad Austral de Chile (47 students) through open-ended surveys, student reports, and the *Students' Perception of Teaching Survey (SPOTs)* at FIU [8]. Results demonstrated that 91% of the students reported an improved comprehension of the balancing procedure.

Taken together, these initiatives demonstrate both the pedagogical potential of virtual laboratories in Mechanical Vibrations and the current limitations related to realism, data handling, and ease of configuration. Building on these insights, the Virtual Mechanical Vibrations Labs (VMVLabs) introduced in this work are designed to provide a low-cost, configurable, and concept-focused platform that more closely aligns with ABET-oriented learning outcomes, as detailed in the following section on their design and development.

III. Design and development of Virtual Labs

The initial VMVLabs platform is designed to simulate a universal benchtop apparatus for the analysis of free and forced vibrations in 1-DoF. The design is inspired on the universal benchtop unit developed at the *Laboratorio de Dinámica de Máquinas de la Universidad Simón Bolívar,* as shown in Figure 1, which served as the primary reference for this virtual implementation. The physical setup comprises the following components according to [9]:

1. One rigid beam with one end pinned and one end supported by a helicoidal spring attached to the ground.
2. A mass attached to a certain distance from the pin end of the bar.
3. One viscous damper attachable to the beam to test responses with damping.

This reference used this equipment for three main experiments related to the following topics, respectively: Free Vibrations, Harmonical Forced Vibrations for 1DoF systems and Forced Vibrations for 2DoF systems.

The implementation of physical laboratories requires specialized equipment, including oscilloscopes, accelerometers, vibrometers, motors, frequency variators, optical sensors, and low-pass filters. By reducing dependence on such physical components, virtual laboratories offer a cost-effective and simpler option that can serve as an alternative or complementary resource to traditional laboratories, with strong potential for broader classroom adoption.

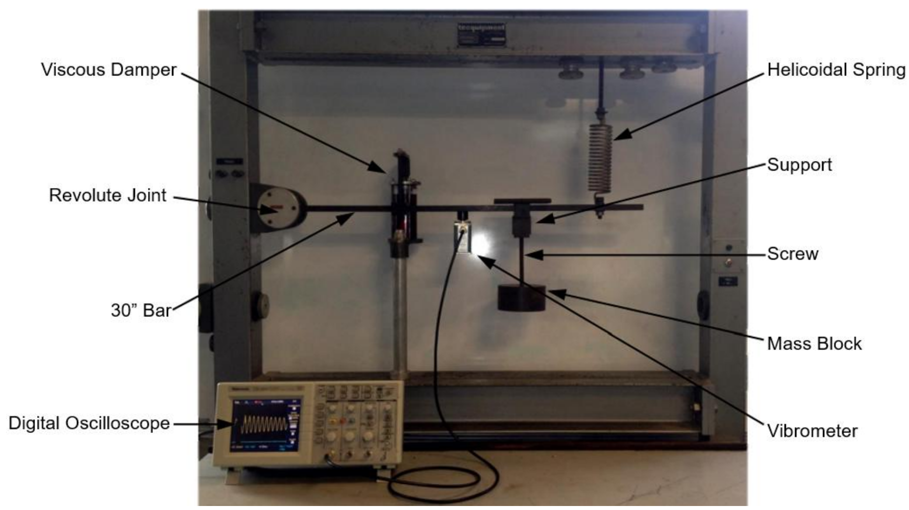


Figure 1: Experimental Set-Up for Lab 1 [9]

General Scheme for VMVLabs

For this virtual tool, the experiments were initially organized into the following three labs, with an additional lab for 2-DoF systems planned for future development:

- Lab 1: Analysis of Free Vibrations, undamped and damped.
- Lab 2: Analysis of a Harmonically Forced System, undamped and damped.
- Lab 3: Analysis of the response of a Step Force, undamped and damped.

All virtual laboratories open with a welcome window that lists the software dependencies of the VMVLabs platform. As shown in Figure 2, this window credits the PyChrono core libraries (math, os, multiprocessing, pygetwindow, matplotlib) and notes that VMVLabs is released as open-source software under the BSD-3-Clause license.

In all labs, the system consists of a rigid beam pinned at one end with a mass attached at the opposite end, as shown in Figure 3. The beam geometry and material follow the reference system given in [9] (**length 80 cm, width 1.27 cm, height 2.54 cm, density 7850 kg/m³**), while a **15 kg tip mass** was chosen arbitrarily.

Each lab includes multiple configurations so that different student teams work with slightly different setups. The spring and damper locations and their parameter values vary across configurations, as described in the following sections.

Figure 2: VMVLabs' Welcome Window

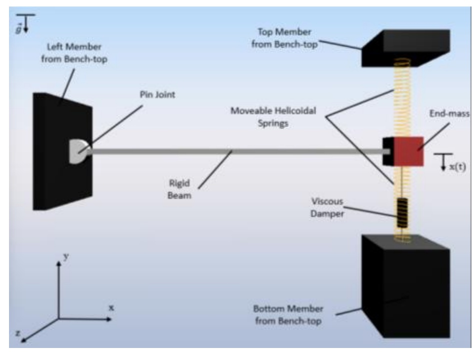


Figure 3: Virtual Benchtop with Articulated Beam

IV. Description and learning objectives of each of the Virtual labs

A. Lab 1: Analysis of Free Vibration

Lab 1 simulates the dynamic response of an articulated beam subjected to **free vibration** (Fig. 4**).** In this context, the beam is released from specified initial conditions—namely, an **initial displacement (x_o)** and an **initial velocity (v_0)**—and no external loads are applied.

The learning objectives of this lab are the following:

1. Understand the physical behavior of free vibration of undamped and damped single-degree-of-freedom (SDOF) systems.
2. Derive the equation of motion of a SDOF system, consisting of a rotating bar, with springs and a damper, with a static equilibrium position when the bar is horizontal.
3. Evaluate damping effects by calculating the damping ratio from decay envelopes or logarithmic decrement.
4. Determine the period of vibration, and calculate the natural frequency, damped frequency
5. Characterize the system by finding the spring and damper coefficients.
6. Relate theoretical predictions with experimental or simulation results.

Lab 1's CONFIGURATION section includes the option to enable or disable damping, define x_o and v_0, and specify the location of the springs by selecting the desired *Configuration*. As shown in Figure 4, the control buttons "Run" and "Exit" are located in the CONFIGURATION section along with the “Update” button, which applies the selected parameters without initiating the simulation to display a preview of the system to simulate.

For this laboratory exercise, four distinct configurations—each examined both with and without damping—were developed to assign slightly different systems to different students’ teams, changing the top spring’s position relative to the planar articulation of the beam. In **Configuration I**, the top spring is located at the beam tip or 100% of the beam length from the articulation, while **Configuration II** locates the spring at three-quarters of the beam length, **Configuration III** at one-half, and **Configuration IV** at one-quarter. These variations change the system’s equivalent stiffness and increase the diversity of observed dynamic responses to be assigned to different students’ groups.

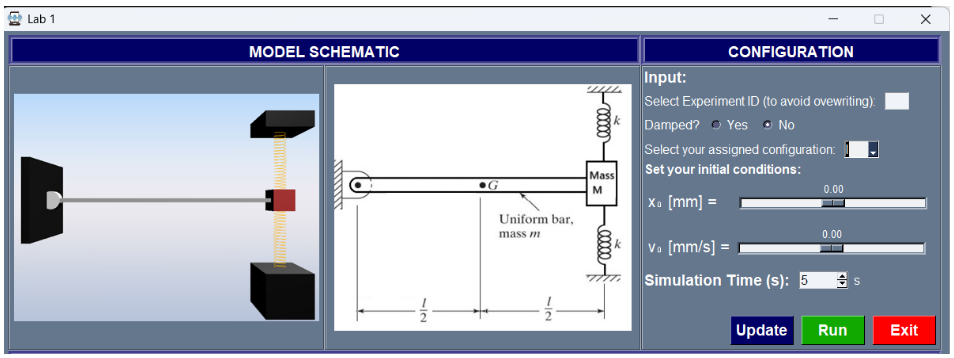


Figure 4. Lab 1 Window

The student can select “Yes” in response to the “Damped?” prompt to enable damping. This action introduces a 40 $\mathrm{N \cdot s \cdot m^{-1}}$ damper at the tip of the beam. The numerical value of the damper coefficient and the stiffness of the springs are expected to be found by the students, as Lab 1 aims to teach how to characterize vibrational systems. To do so, the simulation is executed by clicking on “Run” opening the simulation and the real-time plot shown in Figure 5.

The equation of motion of the damped system can be expressed as:

$$\left(\frac{m_{beam}}{3}+m_{end}\right)\ddot{x}+c\dot{x}+k\left(\left(\frac{d}{L}\right)^2+1\right)x=0 \qquad (1)$$

where **d** represents the fraction of beam length where the top spring is located from the articulation. The position of the upper spring varies depending on the different configuration. To have a system that can be linearized for small displacements, a parametric study was conducted to select the maximum initial displacement, x_o, and initial velocity, v_o, that ensures the maximum amplitude of the response to be $X_o < L\sin(5°)$.
Upon completion of the simulation, the file ***“Free_Vibration_Total_Response_[Experiment Number].txt”*** containing the time history of the beam tip’s y-position is automatically generated. This dataset is subsequently used to plot the response of the system on the software’s home page.

Students use the embedded plotting toolbar or any other software like Excel or MATLAB to navigate the graph and extract the oscillation period. In the undamped case, the natural frequency is determined and employed to calculate the **equivalent system stiffness (k_{eq})**, and consequently the **spring stiffness (k)**. For the damped case, the logarithmic decrement method is applied to estimate the **damping ratio (ξ)**. Using this ratio with the experimentally obtained damped **frequency (ω_d)**, students evaluate both the spring stiffness (k) and the viscous **damper coefficient (c)**, thereby fully characterizing the system's dynamic parameters.

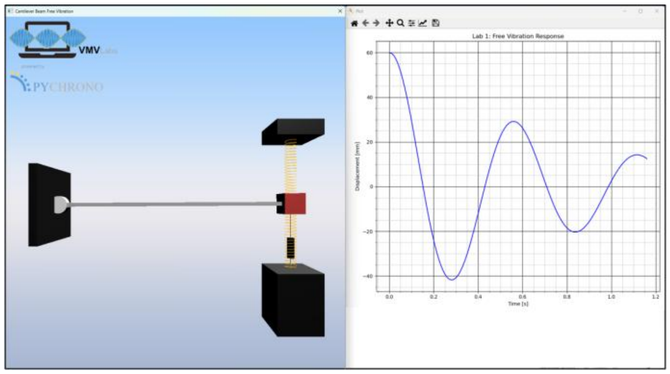


Figure 5: Simulation Execution with 3D Visualization (Left) and Real-Time Plot (Right)

B. Lab 2: Analysis of the Response for Forced System: Harmonic Force

Labs 2 and 3 investigate the dynamic response of the system, but under **forced vibration**. In these experiments, the system is not subjected to any initial displacement or velocity. Instead, external excitation is applied in the form of a **harmonic force (Lab 2)** or a **step force (Lab 3)**. Lab 2 is designed to investigate the nature of transient and steady-state responses and to assess the role of damping in governing the transition between these regimes. Furthermore, the lab seeks to deepen the understanding of resonance and to identify critical operating frequencies through an analysis of the relationship between the **magnification factor (M)** and the **frequency ratio (r)** for both undamped and underdamped systems. To do so, this lab is divided into three parts with the respective learning objectives as follows:

A) Analysis of total response.

1. Understand the total response of a system subjected to harmonic forces.
2. Determine the time needed to reach the steady state response for different damping coefficients.
3. Determine the value of the amplitude for the steady state response.

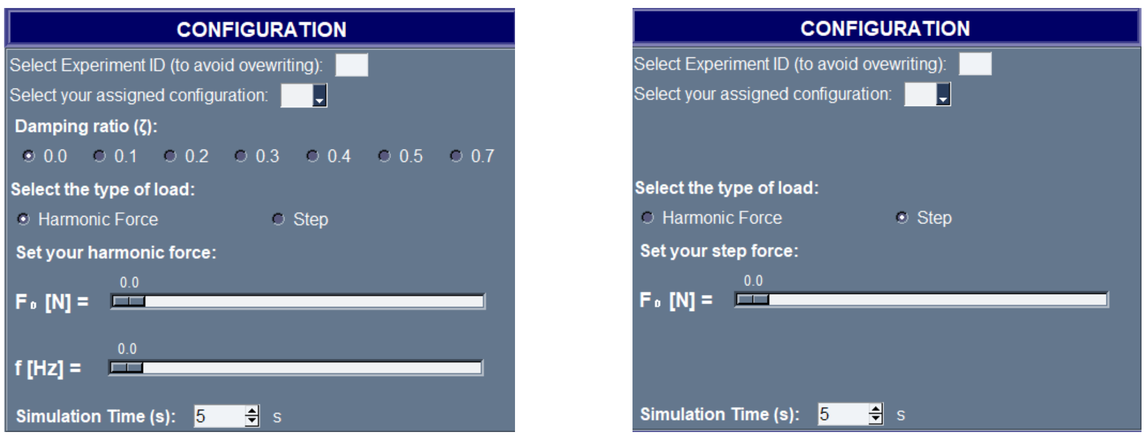
B) Steady-state Harmonic Forced Vibration response for an undamped system

1. Derive the equation of motion of a SDOF subjected to external forces.
2. Interpret the steady state behavior on an undamped system subject to harmonic forces.
3. Determine the resonance frequency by plotting the amplitude of response vs. frequency.
4. Characterize the system by calculating the spring constants.

C) Steady-state Harmonic Forced Vibration response for an underdamped system

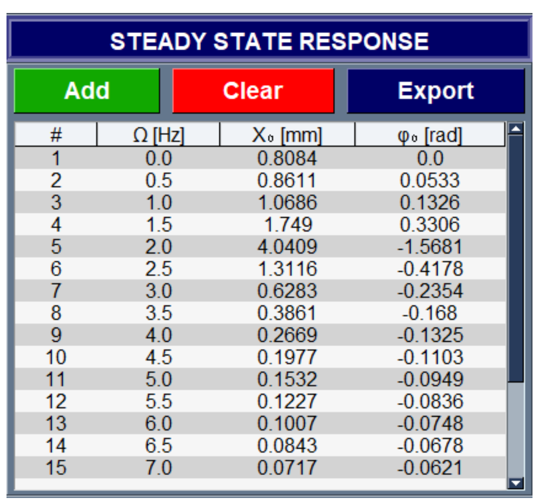
1. Understand the steady-state behavior of an underdamped system.
2. Interpret the relation of the Magnification factor (M) with frequency ratio (r) for several damping coefficients ζ.
3. Interpret the relation of the **phase angle (φ)** with frequency ratio (r) for several damping coefficients ζ.
4. Assess practical implications of forced vibrations in engineering design, such as avoiding resonance and improving system stability.

For a forced vibrating system, the user selects either a harmonic force or a step force (as shown in Figure 6). In the case of a harmonic load, the damping ratio (ζ), **force amplitude (F_0)**, and **operational frequency (Ω)** can be specified. Four configurations were generated with different spring coefficients. It is important to note that spring values are not disclosed to the students beforehand, as the objective of the labs is to experimentally characterize the system.



a) **b)**

Figure 6: CONFIGURATION section for Lab 2 and 3. a) Harmonic Force, b) Step Force



#	Ω [Hz]	X_0 [mm]	$φ_0$ [rad]
1	0.0	0.8084	0.0
2	0.5	0.8611	0.0533
3	1.0	1.0686	0.1326
4	1.5	1.749	0.3306
5	2.0	4.0409	-1.5681
6	2.5	1.3116	-0.4178
7	3.0	0.6283	-0.2354
8	3.5	0.3861	-0.168
9	4.0	0.2669	-0.1325
10	4.5	0.1977	-0.1103
11	5.0	0.1532	-0.0949
12	5.5	0.1227	-0.0836
13	6.0	0.1007	-0.0748
14	6.5	0.0843	-0.0678
15	7.0	0.0717	-0.0621

Figure 7. STEADY-STATE RESPONSE Calculator

Lab 2 also incorporates an additional section titled STEADY-STATE RESPONSE shown in Figure 7, functioning as calculator to quickly determine the amplitude and phase angle of the system's response without initiating any visualization. Selecting the "Export" button generates a file named ***"Amplitude_vs_Freq[Experiment Number].txt"*** which can be processed using any other software (as for example Excel or MATLAB) to get **M vs. r** and **Phase Shift ($\boldsymbol{\varphi}$) vs. r** plots.

C. Lab 3: Analysis of the response for the System subjected to a Step Force

Lab 3 analyzes the same system considered in Lab 2; however, the system is subjected to **a non-periodic step force**. Four new configurations were generated by varying the spring and damper coefficients, as in Lab 2, the spring values are not disclosed to the students beforehand, as the objective of the labs is to experimentally characterize the system.

The learning objectives of this lab are the following:

1. Understand the transient response of a system subjected to a step function.
2. Determine the overshoot, and the time that it takes to reach it, so called peak time.
3. Characterize the system finding spring and damper constants by using the response.

After students select "Step" in the CONFIGURATION section, they must indicate the amplitude of the step function $F(t) = F_o u(t)$ and obtain the response of the concentrated mass. The oscillation period is obtained from the response, allowing the determination of the **damped frequency ($\boldsymbol{\omega_d}$)** and the corresponding **peak time ($\mathbf{t_p}$)**. The **peak displacement ($\mathbf{x(t_p)}$)** and the **steady-state value ($\mathbf{x}(\infty)$)** are then measured to calculate the **maximum overshoot ($\mathbf{M_p}$)**. This overshoot allows for estimating the damping ratio. With the damping ratio and the damped frequency experimentally derived quantities, the system can be fully characterized by finally finding the natural frequency, spring stiffness, and damper coefficient.

V. Implementation

Before using the labs as classroom learning tools, the three modules were pilot tested by the authors and three learning assistants, who executed all configurations. The learning assistants were undergraduate students who had previously completed the course with outstanding performance on assignments and exams. In this preliminary evaluation, all users were able to characterize the system by estimating the spring and damper constants within 0.5–4% of their actual values for all labs.

The labs were then integrated into a 62-student undergraduate Mechanical Vibrations course in the fall 2025 term. In all prior offerings of this course, instruction consisted of lectures and problem-solving activities only; there were no in-person or virtual laboratory components dedicated to studying fundamental vibration concepts.

The Vlabs aimed to strengthen the understanding of the concepts involved in free vibration, and the responses of systems subjected to harmonic or step- forces. To evaluate usability and student perceptions, several instruments were used: 1) An anonymous *System Usability Scale (SUS)* survey administered at the end of the course, 2) Reports for the labs, 3) final grades and exam grades compared to previous terms.

Students were divided into groups of three or four, for 19 teams. For three different assignments, each as part of a module to the corresponding topic, they were asked to perform the labs, and a user Manual was provided. Each team was assigned a different configuration. Each team had to submit a report following a provided template, and all calculations to characterize the system were required.

VI. Results

A. Survey assessing the Virtual labs

The first instrument is the Survey, consisting of ten statements and an open-ended question, administered to the participants at the end of the term. They were asked to evaluate each statement using a Likert four-level scale to express their level of agreement or disagreement. Table 1. shows the questions for the Survey and results. The questions assessed the usability and clarity, (Q1, Q2, Q3), usefulness in the learning process (Q4, Q5, Q6, Q10), user confidence (Q6, Q7, Q8), efficiency and performance (Q1, Q9).

Table 1. Student survey items and response distributions.

Question:	Agree	Somewhat Agree	Somewhat disagree	Disagree
Q1: The virtual labs were easy to download and install.	64.4%	24.4%	4.4%	6.7%
Q2: The virtual labs were easy to use.	53.3%	40.0%	6.7%	0.0%
Q3: The labs are too difficult for the level of this course. I needed technical support to install and to run the labs.	4.4%	17.8%	22.2%	55.6%
Q4: The labs helped me to relate the mathematical equations covered in the course to a real example of a vibrating system.	64.4%	31.1%	4.4%	0.0%
Q5: The labs helped me to understand fundamental concepts of Mechanical Vibrations, such as natural frequency, damped frequency, damping ratio, response of a vibrating system.	73.3%	26.7%	0.0%	0.0%
Q6: All concepts that students were asked to calculate in the lab were covered in the course lectures or examples videos.	77.8%	22.2%	0.0%	0.0%
Q7: The different functions in the virtual labs (e.g., selecting experiment ID, running	75.6%	20.0%	2.2%	2.2%

configurations, changing damping ratios) were well integrated and easy to do..				
Q8: The Manuals and the Template to submit results for the virtual labs were clear, well-structured and provided enough guidance to do the labs.	77.8%	17.8%	4.4%	0.0%
Q9: The program execution time represents a limitation of the use of this software (it is too heavy, or it is too slow).	17.8%	17.8%	31.3%	31.3%
Q10. The labs were a great resource to help understand Mechanical Vibration concepts.	68.9%	26.6%	4.4%	0.0%

The survey results indicate strong student acceptance and perceived educational value of the Virtual Mechanical Vibrations Labs. A large majority of students agreed or somewhat agreed that the labs were easy to download and install (88.8%) and easy to use (93.3%), suggesting a low technical barrier to adoption. Responses to negatively framed questions further support this finding, as 77.8% of students disagreed or somewhat disagreed that the labs were too difficult for the course level or required technical support, which confirms clarity and user confidence.

Importantly, usefulness in the learning process was confirmed since students reported significant pedagogical benefits: over 95% agreed or somewhat agreed that the labs helped relate mathematical formulations to physical vibrating systems, and 100% indicated improved understanding of fundamental concepts such as natural frequency, damping ratio, and system response. High levels of agreement were also observed regarding alignment with course lectures, clarity of manuals, and integration of lab functions.

While a subset of students perceived execution time as a potential limitation, the overall results demonstrate that the virtual labs are both usable and effective.

In addition, it is important to notice the students' opinions expressed in the open-ended question:**Q11: What was most helpful about the virtual labs?** *Out of 45 responses, these five reflect the most common opinions:*

"How easy to use they were and the instructions the professor provided."

"Being able to visualize the system's vibration."

"Interacting with my classmates to complete the labs."

"It gave a better understanding of certain topics with examples and practice."

"The virtual labs were easy to download, run, and analyze data from. They facilitated beneficial assignments for the course."

"The labs didn't run across operating systems. Though it usually worked on windows, my friend's computer is a windows machine and he couldn't get the second/third lab to run. Also, my

computer would sometimes mark the file as a virus (I assume this was due to the pre-compiled binaries)."

B. Lab reports submitted by students' groups

The second instrument is the reports submitted by the students' teams. For Lab 1: Free Vibration,12 teams calculated the spring constant within 4 % error, 5 presented a relatively good report but mixed the concept of k_eq with k, and 2 teams represented a very poor report.

Figure 8 shows the free response shown by group 19 used determine the constant of the spring and the damper by logarithmic decrement.

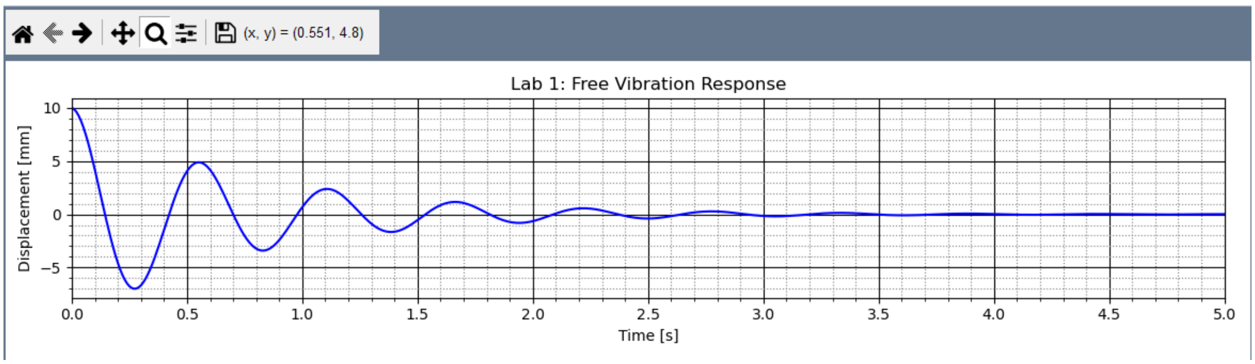


Figure 8. Free response submitted by Team 19

The Lab 2 Harmonically Forced Vibrations, is the longest lab with three different parts, 12 teams presented between excellent and good reports, and calculated the spring constant within 4 % error, 5 teams presented a relatively good report but higher errors or did not complete the three parts. Two teams represented inferior reports with wrong analysis.

Figure 9 shows graphs of Amplitude vs Frequency presented by two different student groups. These graphs were used to calculate the natural frequency of the system with an understanding of the concept of resonance. Since the mass is given, they could calculate the constant of the spring.

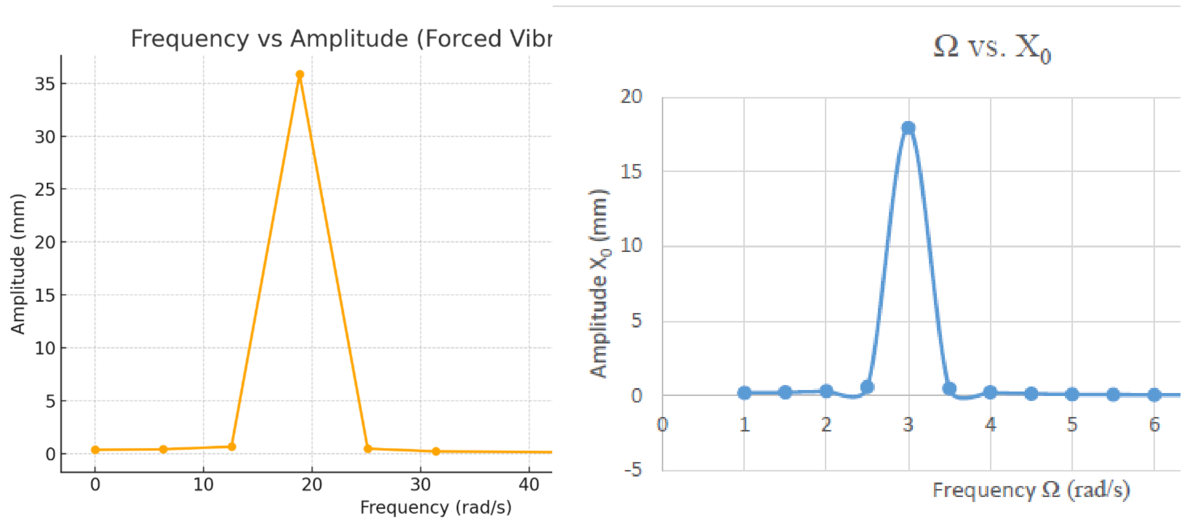


Figure 9 . Amplitude vs. frequency submitted by two different student groups.

For Lab 3, which analyzes the system response to a step input and is the shortest module, 14 teams submitted excellent or good reports and estimated the spring constant within 4% error. Three teams produced relatively good reports, while two teams submitted very poor reports.

C. Comparison of grades for five consecutive terms

Analysis of student performance across five consecutive academic terms is shown in Figure 10. The gradual increase in grades may be attributed to the fact that, since the first term this course was offered by one of the authors in fall 2023, many different educational tools were implemented term by term, such for example: conceptual quizzes after each module, review quizzes before each exam, discussion forums with real case scenarios, group assignments, videos of solving problems, etc. These tools are not explained in detail in this document, because they are out of the scope of this paper, however, are mentioned as an explanation of the steady improvement in course outcomes. Moreover, the largest gains is shown in Fall 2025, when the Virtual Mechanical Vibrations Labs were implemented.

Homework and exam averages increase gradually from Fall 2023 through Spring 2025, followed by a marked jump in Fall 2025: Exam 1 and Exam 2 means rose to 80.2 and 79.9, respectively, compared to values in the low-to-mid 60s and 70s in previous terms. The overall final course average increased from 66.3 in Fall 2023 to 80.7 in Fall 2025, a 14.4-point gain, with more than one-third of this improvement occurring between Spring 2025 and Fall 2025. These trends suggest that integrating interactive virtual labs supports higher conceptual understanding and exam performance by helping students link mathematical formulations to physical system behavior, although additional factors may also contribute to the observed improvements. The improvement in student performance has significantly increased between Fall 2023 and Fall 2025; consequently, we may expect a plateau behavior or a less significant improvement in future terms.

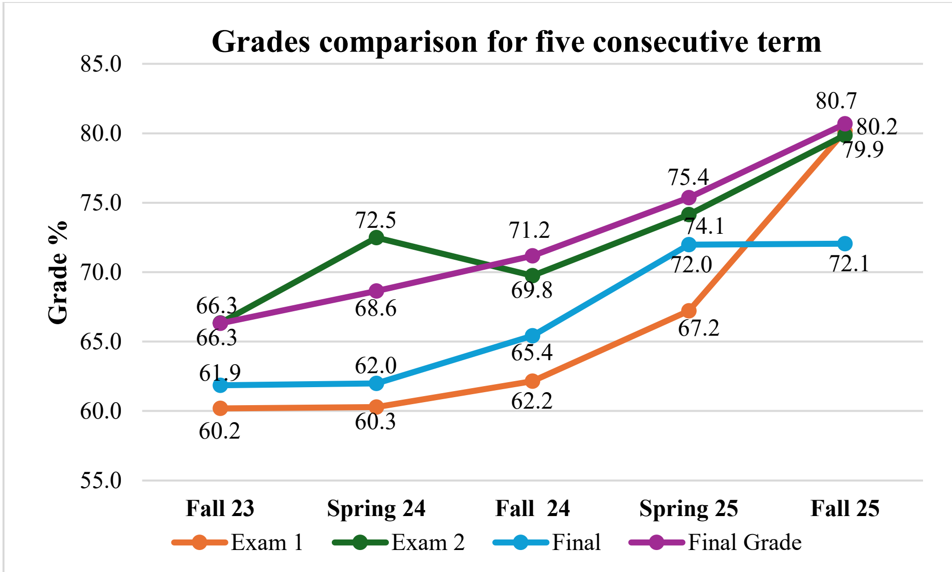


Figure 10. Mechanical Vibration course grades comparison for five consecutive terms.

VII. Conclusions

The end-of-term survey results indicate that the virtual labs exhibit strong learnability and impose a low cognitive and technical load. Students perceived the labs as coherent, consistent, and well aligned with course content, although responses about execution time point to efficiency as a potential area for improvement.

Analysis of overall grades across five consecutive terms shows a clear upward shift in student performance after the introduction of the Virtual Mechanical Vibrations Labs in Fall 2025, with gains distributed across the cohort rather than concentrated among high-performing students. Taken together, these results suggest that VMVLabs function as a valuable instructional supplement that enhances conceptual understanding while remaining accessible in large undergraduate courses.

Since the virtual labs are developed in the PyChrono open-source environment, as a standalone application, this education tool could be easily scalable to other mechanical vibration courses internally or externally to other institutions.

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