Enhancing Mechanical Vibration Education through Virtual Labs: A Focus on Rotor Balancing

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Abstract:

This study investigates integrating a virtual lab for rotor balancing into mechanical vibration courses to enhance student learning. The Virtual Rotor Kit (VRK) lab allows hands-on experience in balancing techniques without physical constraints, offering immediate feedback and visualization of results. With the Rotor balancing example students will reinforce knowledge of vibration that occurs due to an external, periodic force applied to the rotor, and important concepts such as natural frequency, forcing frequency, frequency ratio, vibration amplitude, phase angle, and resonance and will learn the Influence Coefficient Method for rotor balancing. This study assesses the effectiveness of the virtual lab by evaluating the reports submitted by students for a case study on rotor balancing in two different institutions, Universidad Austral de Chile and Florida International University, and evaluating the learning outcomes and students' performance in fundamental concepts on harmonically force vibrations. Student surveys and feedback are also collected to gauge the perceived impact of the virtual lab on their learning experience. Results indicate virtual labs supplement traditional methods, providing a safe, cost-effective platform for practical learning. This research contributes to innovative engineering education approaches, emphasizing the importance of virtual labs in imparting critical skills.

I. Introduction

The goal of this study is to investigate the potential advantages of integrating virtual labs into mechanical vibration courses, with a specific focus on rotor balancing. Traditional approaches to teaching mechanical vibrations often face limitations in providing hands-on experiences due to practical constraints and safety concerns. Therefore, this research aims to assess the efficacy of a virtual lab, the Virtual Rotor Kit (VRK) [1], in enhancing students' understanding and skills in rotor balancing, addressing these constraints and enriching the educational experience in mechanical vibration courses.

Mechanical vibrations play an important role in mechanical engineering education. Vibrations are inherent in various mechanical systems and structures, impacting their performance, stability, and efficiency. Mechanical vibrations involve the oscillatory motion of mechanical systems, often triggered by external forces or disturbances [2]. This topic exposes students to the process of solving engineering problems through a robust foundation in mathematics. It begins by modeling real-world systems as equivalent mechanical systems, then proceeds to derive mathematical models, solve differential equations, and finally, analyze the solutions to comprehensively understand the system's behavior.

Rotor balancing stands out as an illustration within the realm of harmonically forced vibrations. Unbalance is present in most rotating machinery, compromising system stability, and structural integrity of the unbalance machine or surrounding machines, devices and/or environment [3]. Excessive vibrations not only accelerate wear and tear on components but can also lead to noise pollution and discomfort for operators and nearby individuals. Unbalanced rotors can subject components to unnecessary stress and fatigue, significantly reducing the lifespan of rotating machinery [4], [5].

By studying rotor balancing techniques, engineers can implement preventive measures to extend the longevity of critical components, ultimately leading to increased reliability and reduced maintenance costs. Understanding and implementing effective rotor balancing methods act as a preventive measure, reducing the risk of unexpected breakdowns and ensuring the safety of both the equipment and personnel. This topic provides a tangible and practical context for students to grasp the theoretical foundation of harmonically forced vibrations and apply this knowledge to real-world engineering challenges.

To evaluate the tool, mechanical engineering students at two different institutions, in two different continents, utilized the VRK. The two institutions involve in this research are Florida International University, Miami, Florida, in this paper named as Institution 1, and Universidad Austral de Chile, Valdivia, Chile, named as Institution 2. In each institution, students enrolled in Mechanical Vibrations courses were tasked with conducting the virtual laboratory experiment as part of their assignment. At Institution 1, 33 students participated, while 47 students participated at Institution 2.

The present paper is structured as follows. Firstly, the paper explores the educational advantages of introducing virtual labs in engineering major classrooms. Secondly, the VRK Project is introduced, please note that a previous publication describes the tool extensively [1], therefore only a brief overview will be provided in this document. Following this, a rotor balancing experiment is demonstrated using a single-plane rotor example, and additional capabilities of the virtual rotor test rig are also presented. Next, we present the assessment of the VRK's effectiveness as an educational tool. Finally, we conclude with a summary of key findings, final remarks, and recommendations for further development.

II. Educational Advantages of Virtual Labs in Engineering Education

The incorporation of virtual labs into engineering education brings numerous educational advantages, transforming the traditional learning landscape and enriching the student experience. There are several publications on the advantages of using virtual tools in engineering classrooms, particularly for online courses, [6], [7], [8], [9], [10], [11]. While hands-on activities involving real equipment are essential, it's not always possible to have hardware available. Virtual labs provide a secure and controlled environment for students to engage in hands-on learning experiences without the potential risks associated with traditional physical laboratories. This allows students to experiment, make mistakes, and learn from them, fostering a sense of exploration and curiosity. As stated in [8], “a virtual lab that allows students to actively join in and experience the whole experiment process better helps students master related knowledge and skills.”

One key advantage of virtual labs is their accessibility from anywhere with an internet connection. This flexibility is particularly valuable for students with scheduling constraints or limited access to physical lab facilities, democratizing access to practical learning opportunities and ensuring inclusivity in engineering education. Additionally, virtual labs significantly reduce the costs associated with setting up and maintaining physical laboratories, making practical learning more cost-effective and sustainable for educational institutions.

Virtual labs offer the flexibility to simulate a wide range of scenarios and conditions, exposing students to diverse engineering challenges. This adaptability allows for the exploration of concepts beyond the limitations of physical setups, providing a more comprehensive and dynamic learning experience. Immediate feedback from virtual labs enhances the learning process and allows instructors to monitor and assess students' progress effectively. Performance metrics generated by virtual labs can be utilized for personalized learning strategies."

In a mechanical engineering program, student outcomes [12] should comprise understanding engineering problems, system failure (with clarification on what this entails), as well as getting familiar with common procedures to correct them. While traditional on-site labs remain irreplaceable for some aspects of engineering education, the rise of powerful computer and communication resources is pushing the boundaries of learning. These resources, including virtual and remote labs, offer valuable tools to enrich students' experiences. Unlike real lab setups, these digital environments boast significant flexibility and accessibility. With just an internet connection, students can delve into experiments, analyze data, and explore simulated scenarios that might be impractical or risky in a physical lab setting [9], [10]. This empowers online learning and broadens the scope of educational opportunities for future engineers.

III. Virtual Rotor Kit (VRK) Lab

A rotor test rig is an experimental apparatus designed to study the behavior of rotating machinery (e.g. turbomachines, electric machines). It is mainly designed for the development of academic and research activities, which may comprise one or several of the mechanical engineering fields like dynamics, fluid mechanics, thermodynamics, control systems, solid mechanics and heat transfer [5].

Rotor unbalance is the most typical malfunction in rotating equipment; thus, a rotor test rig's basic feature is to demonstrate experimentally this machine malfunction. Typically, an on-hand laboratory activity (*e.g.* single-plane or two-plane balancing experiment) can be conducted to assist learning experiences related to the aforementioned student outcomes. For instance, Figure 1 illustrates the rotor test rig designed for single-plane balancing experiments installed at Universidad Austral de Chile.

In the article [1], the "Virtual Rotor Kit (VRK) Project" introduces and comprehensively describes the VRK Lab, an innovative application designed to facilitate virtual rotor test rig simulations for balancing experiments in mechanical engineering education. The model in the VRK Lab is based on a rotor test rig inspired by Donald Bently's RK4 rotor kit, a widely utilized commercial platform for rotor testing, as documented in recent research (*e.g.*[13], [14], [15]).

Developed on the PyChrono framework [16], the VRK Lab aims to enhance students' understanding of fundamental concepts such as vibration phenomena, resonance, rotor unbalance response, and support flexibility effects in rotating machinery. Unlike traditional on-site lab experiences, the VRK Lab offers flexibility and offline accessibility, providing a valuable complement to standard mechanical engineering education [1].

Figure 1 Laboratory Rotor Test Rig for Single-Plane Balancing Experiments at Universidad Austral de Chile

Key characteristics of the VRK Lab include its lightweight (<400MB), stand -alone application (for Windows) and user-friendly design, powered by the PyChrono simulation engine. The application is based on the Jeffcott rotor model, incorporating flexible and damped supports, a single correction plane, and constraints for adding trial weights. Operating within a speed range of 0 to 5000 RPM, the VRK Lab allows for both steady and transient operations, offering a versatile learning experience. In comparison to similar applications, the VRK Lab stands out for its emphasis on user accessibility, educational focus, and adaptability to various learning environments. The integration of PyChrono ensures robust simulation capabilities, contributing to the application's effectiveness in conveying complex rotor dynamics concepts to students.

The application has several windows: The first window (Figure 2) is the primary setup window, offering an overview of the rotor test rig and showcasing how the rotor speed changes during a test. This window includes four tabs: "Unbalance Setup," "Supports Setup," "Rotor Speed Profile," and "Outputs," each designed for a specific task in setting up the test. Starting with the "Unbalance Setup" tab, users specify the initial unbalance condition. Users can choose from four configurations of unknown original unbalance or select no original unbalance configuration. This tab allows users to enter trial weights for the single plane, taking into account constraints similar to those in a real rotor test rig. Moving to the "Supports Setup" tab, users can adjust equivalent stiffness and damping coefficients for the rotor supports. While these values remain constant during testing, they offer insights into the impact of coefficient variations on the balancing process.

In the "Rotor Speed Profile" tab, users input the steady-state speed, acceleration rate, deceleration rate, and duration of the steady-state lapse. This tab simulates the motor controller interface, setting the maximum rotor speed at 5000 RPM. Finally, the "Outputs" tab provides configuration options for 3D visualization during testing, graphical data display post-test, and data saving for future reference and analysis. With the test setup complete, the experiment begins to run.

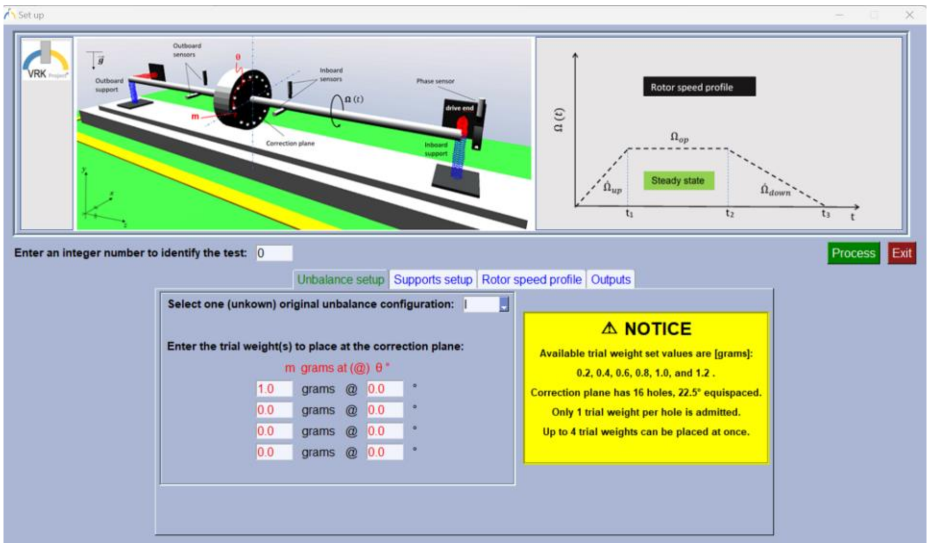


Figure 2 Setup window

As the virtual test runs, two windows may pop up together. The "V-meter window" shows the current rotor speed, elapsed time, and vibration measurements during the steady-state regime. It also presents amplitude and phase measurements at synchronous frequency, fundamental for figuring out correction weights in balancing experiments.

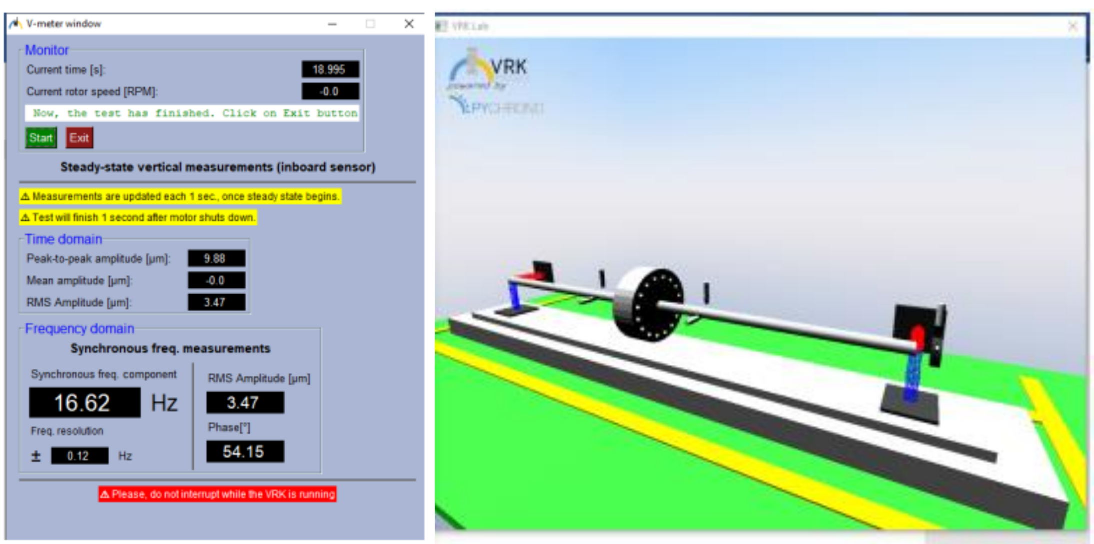


Figure 3 V-meter window, response to initial unbalance

If the user chooses to activate the visualization option, the "VRK Lab" window will appear, offering a 3D interactive representation of the virtual rotor test rig. While it's optional, it provides you with insights into the dynamics of the rig, although with the drawback of a longer execution time.

Once the test concludes, the "virtual orbit window" displays horizontal and vertical vibrations from inboard sensors, along with the shaft's orbit and amplitude variation with rotor speed, see Figure 4. Transient and steady-state measurements are both showcased.

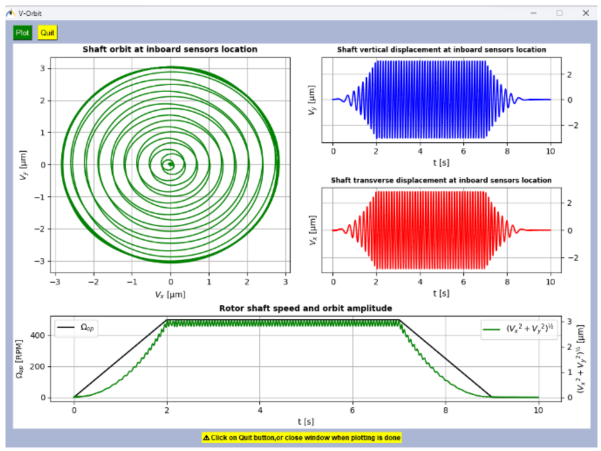


Figure 4 V-meter window, response to initial unbalance

In the next section, we'll explore the VRK's GUI through a hands-on rotor balancing example, providing a clear understanding of its features and functionality.

IV. Rotor Balancing Example

Rotor unbalance is commonly synchronous vibration. The actual balance condition of an assembled rotor is never fully known prior to, during, or after a successful balance procedure is executed either in the shop or field [17], [18], [19]. The only way to assess the unbalance is to add balance correction weights at various locations and measure the vibration reduction, there may be a reasonable residual unbalance that will not be eliminated.

The most basic method for rotor balancing is the single plane balance, and the corresponding correction weight is typically estimated by means of the Method of Influence Coefficient [3], [17], [20]. This method could be applied using, graphical approach or analytical approach. For both approaches the general steps are [17], [21]:

1. Collect reference synchronous vibration amplitude and phase data (V_o, φ_o),
2. Apply a Trial Weight (mr_{TW} φ_{Tw}) and collect response data (V_1, φ_1)
3. Compare initial and trial vibration vectors, calculate the Effect vector amplitude $V_T = ($V1 $-V_o)$, and phase φ_T
4. The influence factor is determined, as the response of the trail weigh $\bar{V}_T$, divided by the known Trail Weight (mr_{TW}) , $\bar{\gamma} = \frac{\bar{V}_T}{mr_{TW}}$.

5. Determine a correction weight by $mr_{CW} = -\frac{V_o}{\gamma}$
6. The angle to place the correction weight is calculated as $\alpha_{cw} = \alpha_o + \alpha_{Tw} - (\alpha_T) + 180°$
7. Validation run, to verify if balancing solution is satisfactory by comparing the vibration amplitude V_2 to the original amplitude vibration V_o.

In the following example, the virtual rotor kit (VRK) is required to be balanced when it runs at 1000 RPM constant speed, and the "original" unbalance configuration is unknown. The tests and solution will be based on the coefficient influence method. Similar to a "real" rotor test rig, constrains must be addressed when the solution is implemented. To add any trial weight to the VRK 's correction plane the constrains shown in yellow in the setup window in Figure 2 have to be taken into account.

Step 1: Select the configuration, rotor speed and output as shown in Figure 2, and collect data. The second window (VRK Lab) is the "virtual" lab showing the VRK operation for the current test. This window is blank until the test begins. Need to click on the Start button to begin the test. The V-meter window is a "virtual" meter to show basic measurements, in time and frequency domains. The VRK calculates the RMS amplitude Collect reference synchronous vibration amplitude and phase data (V_o, φ_o). The RMS amplitude and phase for the synchronous frequency component yield (see Figure 3):

$$V_o = 3.47\mu m \angle \varphi_o = 54.15° \quad (1)$$

This value is the measured vibration (i.e. "original vibration") caused by the original rotor unbalance.

Step 2: Apply a Trial Weight (mr_{TW} φ_{Tw}) and collect response data (V_1, φ_1): mr_{TW} = 1 gr, φ_{Tw}= 0 °, The collected response data (V_1=11.61 μm,$\angle\varphi_1$ = 13.34°) as shown in Figure 5 .

Step 3: Compare initial and trial vibration vectors, calculate the Effect vector amplitude $V_T = (V_1 - V_o)$, and phase φ_T

$$Re(\overline{V_T}) = Re(\overline{V_1}) - Re(\overline{V_0}) = 9.27 \quad (2)$$

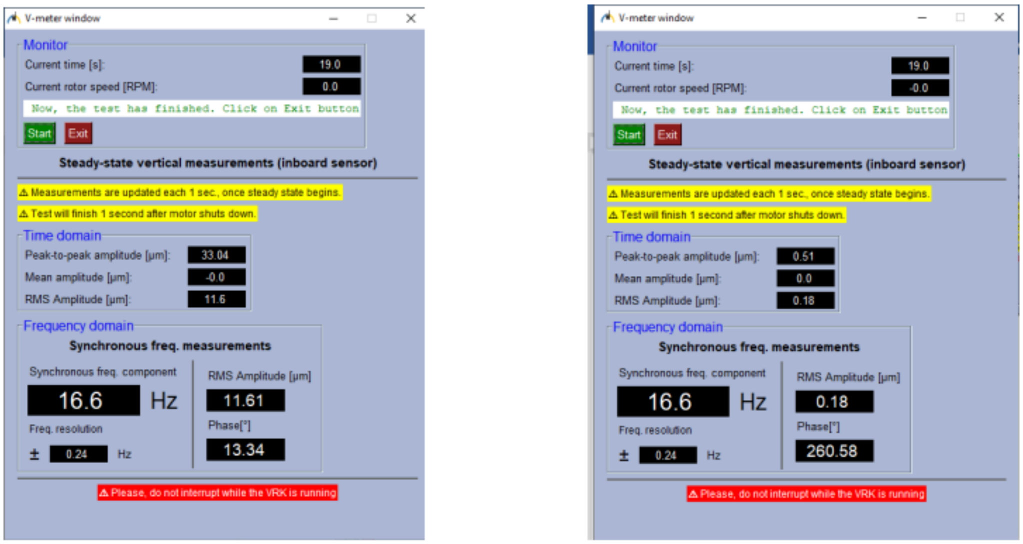
$$Im(\overline{V_T}) = Im(\overline{V_1}) - Im(\overline{V_0}) = -0.13 \quad (3)$$

$$V_T = \sqrt{Re(\overline{V_T})^2 + Im(\overline{V_T})^2} = \mathbf{9.26\ \mu m} \quad (4)$$

$$\varphi_T = tan^{-1}\left(\frac{Im(\overline{V_T})}{Re(\overline{V_T})}\right) = 0.83° \quad (5)$$

Step 4: Calculate the influence coefficient.

$$\bar{\gamma} = \frac{V_T}{mr_{TW}} \text{ at } (\varphi_T - \varphi_{TW}) = \frac{9.26}{1}\angle(-0.83° - 0°) = 9.26\frac{\mu m}{gr}\angle(-0.83°) \quad (6)$$



(a) (b)

Figure 5 V-meter window, a) response to unbalance plus trail weight, b) response to proposed solution

Step 5 and 6: Determine the Correction weight magnitude and angle:

$$mr_{CW} = -\frac{V_O}{\gamma} = \frac{V_O\, mr_{TW}}{V_T} = \overline{mr_{CW}} = 0.37\ gr\ \angle 235° \tag{7}$$

Step 7: Implement solution, and validate.

Due to the constraints of the VRK, the solution cannot be implemented, there is neither 0.37 grams available nor an angular position at 235° to place a trial weight. To overcome those limitations, one practical solution consists in expressing the mr_{CW} as the sum of two unknown weights, placed close to the "ideal" solution.

$$\overline{mr_{CW}} = m_1\ \angle(225°) + m_2\ \angle(247.5°) \tag{8}$$

In this case the closest trial weight value available is 0.2 grams. Concluding, the solution to be implemented is

$$\boldsymbol{m_1} = 0.2 \text{ grams } \angle(\boldsymbol{225}°),\quad \boldsymbol{m_2} = 0.2 \text{ grams } \angle(\boldsymbol{247.5}°) \tag{9}$$

The collected response data (V_2=0.18 µm $\angle\varphi_1 = 260.58°$) as shown in Figure 5 (b).

A significant amplitude reduction is observed, after comparing the RMS amplitudes, at the synchronous frequency component, obtained for the original test and the validation test.

The ratio between those amplitudes is equal to

$$\frac{0.18\ \mu m}{3.47 \mu m} = 5.18\% \tag{10}$$

confirming that the balancing procedure has been satisfactory.

V. Assessment of Virtual Lab Effectiveness

Structuring the assignment for virtual labs appropriately, including lab preparation, team work to support peer learning and discussion it very important for students' engagement**Error! Reference source not found.**in the assignment activity [22]. Mechanical engineering students at the two institutions utilized the Virtual Rotor Kit (VRK). In each institution, 33 students at Institution 1 and a 47 number at Institution 2, enrolled in Mechanical Vibrations courses, were tasked with conducting the virtual laboratory experiment as part of their assignment.

Implementation and results at Institution 1: Florida International University

The assignment is part of the two weeks Harmonically Forced Vibration Module, representing the third topic in the semester, it comes after Module 1, which encompass one week of review of mathematical concepts, and two weeks of Introduction to Vibration Terminology and determining the equation of motion of mechanical system of a single degree of freedom; Module 2 which represents two weeks studying response to free vibrations. For module 3, after covering the main foundations for harmonically forced vibration, including external harmonic forces, base motion and vibration due to unbalance. Rotor balancing is introduced as one of the applications. Students are presented with a lecture on the fundamentals of unbalanced rotating machinery and common techniques for balancing. The VRK is presented, and the example exposed in the previous section was solved for the students in a video.

As an assignment, worth 5% of the total grade of the course, groups of three students were required to install the VRK software in their computers and perform the virtual laboratory following the guidelines presented to the class. The students have also available a video with a tutorial, on how to install and use the tool.

Each team was provided with an arbitrary original rotor unbalance configuration and an operational rotor speed. The objective of the laboratory experience was to apply a single balancing method, following the seven steps described in the previous section, and validate the implemented solution.

Each group had to submit a report with results following a provided template in Word. The report had to show all calculations required to obtain the proposed solution to the unbalance.

To assess the effectiveness of using the VRK as an educational tool, several instruments were used: 1) A survey specifically use to evaluate the tool, consisting of eight statements and an open-ended question, 2) Reports for the Virtual Lab, 3) The SPOTs (Students Perception of Teaching Survey) which is a general anonymous survey distributed to all students for all classes at our Institution.

The first instrument to is the Survey consisting of eight statements and an open-ended question administered to the participants, right after the students submitted the report for the virtual lab. They were asked to evaluate each statement using a Likert scale to express their level of agreement or disagreement. The five-level scale ranged from “strongly disagree” to “strongly agree”. Table 1 show the questions and results:

Table 1 Results for Institution 1 Students Perception of VRK tool Survey

Question:	Strongly agree	Agree	Neither agree nor disagree	Disagree	Strongly disagree
Q1: By using this program, you can gain a better understanding of the single-plane balancing procedure of an unbalanced shaft.	32%	59%	9%	0%	0%
Q2: With the support of the webpage and the tutorial the VRK tool was easy to install.	25%	46%	14%	14%	0%
Q3: The program execution time does not represent a limitation of the use of this software.	9%	55%	27%	9%	0%
Q4: With the support of the webpage and the tutorial the VRK tool was easy to use.	27%	50%	14%	9%	0%
Q5: Vibration measurements are displayed clearly in the V-orbit window	23%	64%	9%	5%	0%
Q6: The VRK lab window provides a visualization of the VRK operation aiding in understanding the rotor balancing procedure.	23%	64%	18%	0%	0%
Q7: The V-meter window clearly displays the measured vibration.	22%	61%	17%	0%	0%
Q8: The main setup window and its tabs clearly request the inputs.	41%	45%	14%	0%	0%

As shown in Table 1 the results for Q1 reveal that 91% of students either "Strongly Agree" or "Agree" that the tool aided them in gaining a better understanding of the single-plane balancing procedure of an unbalanced shaft.

As for Q2, the majority of students find the tool easy to install. However, Q3 indicates that some students perceive the program's time execution as a potential limitation.

The results for Q4 to Q8 indicate that, while the majority of students agree that the windows provide clear visualization of the operation and measurement of vibrations, there is room for improvement in both the installation process and the visualization of results.

Very important to also read the students' opinions in the open-ended question*: Do you have any additional comments? your opinion is very important.* Some of the students' comments are the following:

> *"The opportunity to be encouraged to try new software in the class to get more accustomed to it and try it was a nice addition."*
>
> *"I thought the VRK lab really helped me understand the system. It was really helpful to have a visual representative of the things we were learning in class."*
>
> *"It was a good tool to have during the class to visualize problems better."*

“The learning tool was great! My only problem was setting it up but after that it was very user friendly with the tutorial.”

“I wish you could see the weights on the graphic of the program, I've seen mechanics adding weights to balance wheels in the past, and if you haven't seen or remember seeing something like this working it is hard to understand.

I liked the lab, it provided and understanding of how it works. I was able to download it on a virtual school computer, I was not able to have the program working on my personal computer (the program wouldn't open and gave me this error). I found out later that i could click "take me to error, the program starts.””

The second instrument employed to assess the efficacy of the Virtual Rotor Kit (VRK) as a learning tool was the laboratory report. Out of the 11 teams, six successfully submitted commendable reports, proposing and implementing a solution that reduced the amplitude to 5% of the original unbalanced amplitude. Four groups also submitted reports but fell short of the objective to decrease the amplitude to the specified level. Various reasons contributed to these teams not meeting the requirement, including non-compliance with the constraints of the virtual lab. Lastly, one team did not complete the lab, resulting in a deduction in the assignment grade.

The final tool employed to assess student perception of the Virtual Rotor Kit (VRK) is the Student Perception of Teaching Survey. Students were given the opportunity to respond to 15 questions related to course structure, learning support, and student-instructor interaction, along with open-ended questions expressing their opinions.

The course, Mechanical Vibration, has been delivered as an online course for several semesters. Over the last four terms, the average overall evaluation of the course stood at 4.20 out of 5. Notably, the overall score for the fall 2023 term saw a substantial increase, reaching 4.59 out of 5. While various factors may have contributed to this nearly 0.4-point improvement in the overall score, it is crucial to highlight that the sole addition to the course during this period was the introduction of the virtual lab.

One student mentioned that the collaborative assignments helped with the learning process: *“Interactive assignments, group assignments with classmates, and class discussions helped me understand course work better”.*

Implementation and results at Institution 2: Universidad Austral de Chile

Building on the previous implementation, we assessed the usability and learning effectiveness of the VRK with 47 senior mechanical engineering students from Institution 2. Two instruments were used: the first measured VRK usability, evaluating how students interacted with its features, while the second gauged the VRK Project's effectiveness as a learning tool for balancing methods. This second activity was conducted before an on-site laboratory experience using the rotor test rig illustrated in Fig. 1.

The evaluation process began with an introductory lecture covering unbalance fundamentals and field balancing techniques. During this lecture, the instructor also presented an overview of the application and provided installation guidelines to the students. Table 2 summarizes the survey results for this implementation. Note that, although the same survey was used, questions regarding installation (*i.e.*, Q2 and Q4 in Table 1) were excluded since installation guidance was provided during a dedicated in-class session.

Table 2 Results for UACh' Students Perception of VRK tool Survey

Question:	Strongly agree	Agree	Neither agree nor disagree	Disagree	Strongly disagree
Q1: By using this program, you can gain a better understanding of the single-plane balancing procedure of an unbalanced shaft.	68%	23%	9%	0%	0%
Q3: The program execution time does not represent a limitation of the use of this software.	38%	30%	19%	11%	2%
Q5: Vibration measurements are displayed clearly in the V-orbit window	64%	34%	2%	0%	0%
Q6: The VRK lab window provides a visualization of the VRK operation aiding in understanding the rotor balancing procedure.	64%	25%	9%	2%	0%
Q7: The V-meter window clearly displays the measured vibration.	70%	30%	0%	0%	0%
Q8: The main setup window and its tabs clearly request the inputs.	70%	26%	4%	0%	0%

The open-ended question elicited suggestions for application improvement from participants. Although not all responded, feedback addressed aspects like GUI design and execution time. For instance, some suggestions must be addressed, as they are cited below:

"I think that in case of having to go back, it should be more user-friendly and not have to close everything each time."

"Not a bad idea to have a backup of the data entered at the beginning (or in case it exists, I didn't know how to access it."

"If the goal is to complete an exercise in a short amount of time, it is not very efficient to use a very high speed, as it takes quite a long time to finish the simulation."

The usability evaluation of the VRK revealed both strengths and an opportunity for improvement. According to responses to question Q1, over 90% of students found that the application enhanced their understanding of the single plane rotor balancing procedure. Participants praised the clarity of input requests and measurement displays, finding them easy to understand and navigate. The virtual rotor visualization and accompanying graphs were also appreciated, effectively enhancing learning of the balancing process (*i.e.* results derived from questions Q5 to Q8).

However, one area requiring attention is execution time (results from question Q3). While most found it acceptable, 13% considered it a significant limitation, especially when combined with the visualization and high operational speeds. In fact, tests with speeds approaching the maximum (5000 RPM) could even take over an hour to complete, leading to complaints from some users. Addressing this issue through optimization is crucial to ensure a smooth and efficient learning experience for all users.

Building on their theoretical understanding from the first activity, participants in the second activity put their skills to the test in a virtual laboratory experiment using VRK. Each student tackled a unique scenario with a specific rotor unbalance configuration and operational speed. They were tasked with simulating the standard on-site procedure, proposing a trial weight, calculating the correction weight using the influence coefficient method, and validating their solution through a virtual test. This hands-on experience culminated in each student submitting a concise report summarizing their findings.

The effectiveness of VRK as a learning tool was then evaluated through quantitative analysis of these individual experiments. Focusing on three key aspects mirroring real-world tasks, the analysis revealed:

-Understanding balancing principles: 68% of students scored above average, with many achieving the maximum score, indicating strong theoretical grasp.

-Applying balancing calculations: 59% exceeded the average, demonstrating successful translation of knowledge into practical skills.

-Balancing a rotor within constraints: 56% surpassed the average, showcasing good comprehension and the ability to apply skills in a realistic scenario.

Furthermore, the types of mistakes made during the virtual experiments closely resembled those observed in actual lab settings. This suggests that VRK accurately replicates the challenges and learning opportunities of real-world balancing procedures. Combined with the positive feedback from the usability evaluation, this underscores VRK's potential as a valuable tool for enhancing both understanding and skill development in rotor balancing.

VI. Conclusion

This research showcases the implementation of a virtual rotor balancing lab as an assignment in a mechanical vibration course. This unique hands-on experience allowed students to bridge the gap between theoretical knowledge and practical application. Over 90% of students from two different institutions, surveyed after completing the virtual lab, reported that it significantly improved their understanding of rotor balancing. Furthermore, the results, obtained with both group and individual activity formats in different institutions, highlight the virtual lab's potential to enhance comprehension of rotating machinery dynamics.

The virtual lab represents a very low-cost tool that break down geographical and time barriers. Students from two different institutions, in two different continents, were able to access the Virtual lab remotely, facilitating learning outside traditional classroom hours. This accessibility ensures that students can engage with practical exercises at their convenience, promoting a more flexible and inclusive learning environment.

The implementation of virtual labs opens avenues for ongoing research and development in educational technology. This exploration can lead to the creation of more sophisticated virtual environments, adaptive learning systems, and data-driven insights into student performance, contributing to the continuous improvement of engineering education methodologies.

By adopting virtual labs, engineering education institutions set a benchmark for future innovations in teaching methodologies. The success of virtual labs can inspire further exploration into incorporating cutting-edge technologies and methodologies, fostering a culture of innovation in engineering education.

REFERENCES

[1] L. U. Medina Uzcátegui, C. Müller-Karger Pereda, and E. Casanova Medina, "The Virtual Rotor Kit Project: A virtual rotor test rig for balancing experiments," *International Journal of Mechanical Engineering Education*, p. 03064190231197119, Aug. 2023, doi: 10.1177/03064190231197119.

[2] S. S. Rao and F. F. Yap, *Mechanical vibrations*, vol. 4. Addison-Wesley New York, 1995.

[3] W. C. Foiles, P. E. Allaire, and E. J. Gunter, "Rotor balancing," *Shock and Vibration*, vol. 5, no. 5, 6, pp. 325–336, 1998.

[4] J. M. Vance, *Rotordynamics of turbomachinery*. John Wiley & Sons, 1991.

[5] M. L. Adams, *Rotating Machinery Research and Development Test Rigs*. CRC Press, 2017.

[6] Y. Liu, F. Baker, W. He, and W. Lai, "Development, assessment, and evaluation of laboratory experimentation for a mechanical vibrations and controls course," *International Journal of Mechanical Engineering Education*, vol. 47, no. 4, pp. 315–337, 2019.

[7] Y. Liu, S. Whitaker, C. Hayes, J. Logsdon, L. McAfee, and R. Parker, "Establishment of an experimental-computational framework for promoting Project-based learning for vibrations and controls education," *International Journal of Mechanical Engineering Education*, vol. 50, no. 1, pp. 158–175, Jan. 2022, doi: 10.1177/0306419020950250.

[8] B. Cheng, H. Su, D. Cheng, and X. Luo, "Developing Virtual Labs for Engineering Education: Lessons from Leveling Experiment," in *Proceedings of the 27th International Symposium on Advancement of Construction Management and Real Estate*, J. Li, W. Lu, Y. Peng, H. Yuan, and D. Wang, Eds., in Lecture Notes in Operations Research. , Singapore: Springer Nature Singapore, 2023, pp. 96–103. doi: 10.1007/978-981-99-3626-7_8.

[9] L. Rassudov and A. Korunets, "Virtual Labs: An Effective Engineering Education Tool for Remote Learning and not only," in *2022 29th International Workshop on Electric Drives: Advances in Power Electronics for Electric Drives (IWED)*, IEEE, 2022, pp. 1–4. Accessed: Jan. 17, 2024. [Online]. Available: https://ieeexplore.ieee.org/abstract/document/9722375/

[10] B. Balamuralithara and P. C. Woods, "Virtual laboratories in engineering education: The simulation lab and remote lab," *Computer Applications in Engineering Education*, vol. 17, no. 1, pp. 108–118, 2009.

[11] A. Van Den Beemt, S. Groothuijsen, L. Ozkan, and W. Hendrix, "Remote labs in higher engineering education: engaging students with active learning pedagogy," *J Comput High Educ*, vol. 35, no. 2, pp. 320–340, Aug. 2023, doi: 10.1007/s12528-022-09331-4.

[12] Accreditation Board for Engineering and Technology, "Criteria for Accrediting Engineering Programs, 2022 - 2023," ABET. Accessed: Jan. 18, 2024. [Online]. Available: https://www.abet.org/accreditation/accreditation-criteria/criteria-for-accrediting-engineering-programs-2022-2023/
[13] X. Zhang, Y. Yang, M. Shi, A. Ming, and P. Wang, "Novel energy identification method for shallow cracked rotor system," *Mechanical Systems and Signal Processing*, vol. 186, p. 109886, 2023.
[14] Z. Jia, Y. Yang, Q. Zheng, and W. Deng, "Dynamic analysis of Jeffcott rotor under uncertainty based on Chebyshev convex method," *Mechanical Systems and Signal Processing*, vol. 167, p. 108603, 2022.
[15] H. Yao, Y. Wang, Y. Cao, and B. Wen, "Multi-stable nonlinear energy sink for rotor system," *International Journal of Non-Linear Mechanics*, vol. 118, p. 103273, 2020.
[16] A. Tasora *et al.*, "Chrono: An open source multi-physics dynamics engine," in *International Conference on High Performance Computing in Science and Engineering*, Springer, 2015, pp. 19–49.
[17] N. F. Rieger, *Balancing of rigid and flexible rotors*. Shock and Vibration Information Center, US Department of Defense, 1986.
[18] R. Kelm, W. Kelm, and D. Pavelek, "Rotor Balancing Tutorial," in *Proceedings of the 45th Turbomachinery Symposium*, Turbomachinery Laboratories, Texas A&M Engineering Experiment Station, 2016.
[19] D. Childs, *Turbomachinery rotordynamics: phenomena, modeling, and analysis*. John Wiley & Sons, 1993.
[20] M. L. Adams, : *From Analysis to Troubleshooting, Second Edition*, 2nd ed. Boca Raton: CRC Press, 2009. doi: 10.1201/9781439847558.
[21] A. Muszynska, *Rotordynamics*. CRC press, 2005.
[22] E.-S. S. Aziz, S. K. Esche, and C. Chassapis, "Content-rich interactive online laboratory systems," *Computer Applications in Engineering Education*, vol. 17, no. 1, pp. 61–79, 2009.