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A Scalable Open Educational Resource and Laboratory-Integrated Approach to Undergraduate Vibrations Education

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Abstract

Undergraduate vibrations courses are often delivered primarily through lecture, with limited experimental integration due to the high cost of traditional vibration laboratory equipment. This paper presents the development and evaluation of a full-semester undergraduate vibrations course that integrates a structured progression from theory to experiment while reducing laboratory implementation costs from the typical $20,000–$40,000 range to under $5,000.

The course begins with an openly authored open educational resource (OER) textbook introducing foundational vibration theory. Students then engage with instructor-developed video lectures, worked examples, and Mathematica analysis notebooks that support visualization of free and forced vibration, damping, resonance, and modal behavior. Custom interactive Mathematica Demonstrations enable real-time parameter exploration prior to hands-on experimentation. Laboratory activities utilize wireless accelerometers, force sensors, portable data acquisition (DAQ) interfaces, and modular 3D-printed fixtures, allowing students to observe vibratory phenomena directly and compare measured responses with analytical and computational predictions.

A central feature of the course is accessibility for students with varied mathematical preparation. Physical intuition is developed through visualizations, simulations, and guided analysis before formal derivations are emphasized. Assessment data, including rubric-based evaluations, behavioral performance metrics, and pre- and post-course conceptual measures, indicate attainment of targeted learning outcomes and increased student confidence in computational modeling, instrumentation, and vibration analysis.

This structured, OER-based framework demonstrates that resource-constrained programs can deliver rigorous, laboratory-integrated vibrations instruction using affordable instrumentation. The model is replicable and supported by openly available instructional materials, providing a practical pathway for broader adoption.

Introduction

Vibrations is a foundational subject in mechanical engineering and is central to the analysis and design of dynamic systems, structural components, rotating machinery, automotive suspensions, aerospace structures, and numerous engineered products [1–3]. Despite its importance, undergraduate vibrations courses are frequently delivered with limited experimental integration, relying primarily on mathematical derivations and problem sets rather than structured hands-on investigation [4]. Traditional vibration laboratory systems, including modal shakers, laser vibrometers, instrumented beam assemblies, and commercial data acquisition platforms, are costly and often exceed the financial capacity of resource-constrained programs [5, 6].

Recent studies emphasize the importance of strengthening experiential learning in vibrations education, noting that structured laboratory engagement promotes deeper conceptual understanding, reduces persistent misconceptions, and improves students' ability to relate theoretical models to physical system behavior [7–9]. Experimental activities require students to confront measurement uncertainty, parameter identification, model validation, and nonlinear or noisy responses that are seldom addressed in purely analytical coursework [10]. These experiences align with ABET Student Outcomes emphasizing experimentation, data analysis, and the application of engineering judgment [11].

Despite these recognized benefits, cost remains the primary constraint limiting broader adoption of laboratory-based vibrations instruction. Surveys of mechanical engineering curricula indicate that only a small fraction of programs offer a dedicated undergraduate vibrations laboratory, with many institutions relying instead on demonstration-based setups or incorporating limited experiments within lecture courses [12, 13]. Conventional equipment budgets for a fully equipped vibrations laboratory typically range from approximately $20,000 to more than $40,000, placing high-fidelity experimental infrastructure beyond the financial reach of many departments [6, 14]. In response, several researchers have proposed low-cost, portable, and modular laboratory platforms intended to expand access to meaningful vibrations experimentation across a wider range of institutions [15–17].

Concurrently, OER and open-source computational tools have emerged as mechanisms for increasing accessibility in engineering education. Freely available textbooks, simulations, code examples, and interactive digital environments reduce direct student costs while supporting flexible and equitable learning structures [18–20]. Meta-analyses of OER adoption report that student outcomes are maintained or improved while overall course affordability increases substantially [21, 22]. The integration of OER-based instructional materials with low-cost experimental hardware has therefore been identified as a promising pathway for broadening access to laboratory-intensive STEM curricula [23].

Computational tool selection likewise plays an important role in vibrations instruction. Traditional course sequences often rely on MATLAB for numerical modeling; however, software licensing requirements may restrict access at institutions with limited resources. Prior studies indicate that Mathematica, Python, and other open or institutionally supported platforms provide robust environments for symbolic derivation, numerical simulation, and frequency-domain analysis when supported by appropriate instructional scaffolding [24–26]. Interactive modeling environments, including those distributed through the Mathematica Demonstrations Project, enable real-time visualization of vibratory systems and have been shown to strengthen student understanding of modal behavior, damping, and parameter sensitivity [27–29]. When integrated with laboratory activities, these computational tools establish a coherent progression from theoretical development to experimental validation and model refinement.

Student preparation presents an additional challenge in vibrations instruction. Learners often enter the course with uneven backgrounds in differential equations, linear algebra, and systems modeling. Prior research indicates that such disparities can limit engagement and performance in mathematically intensive subjects [30]. Scaffolded instructional approaches, in which physical intuition is developed through conceptual visualization and guided experimentation prior to formal mathematical derivation, have been shown to support students with varied preparation in dynamic systems courses [31–33].

This paper presents the design and assessment of a comprehensive undergraduate vibrations course that integrates OER-based theoretical instruction, Mathematica-based computational modeling, low-cost laboratory hardware, and modular 3D-printed experimental fixtures. The course reduces equipment costs from the typical $20,000–$40,000 range to under $5,000 while providing structured experimental experiences in free vibration, forced response, damping, resonance, and modal analysis. Instruction follows a deliberate progression from conceptual foundations, supported by OER materials and instructor-developed multimedia resources, to symbolic and numerical modeling in Mathematica, and culminates in hands-on experimentation using wireless sensors and portable data acquisition interfaces. Assessment results indicate attainment of targeted learning outcomes and increased student confidence in computational modeling, instrumentation, and vibration analysis. The resulting framework offers an affordable, scalable, and replicable model for institutions seeking to implement laboratory-integrated vibrations instruction under resource constraints.

Course Design and Implementation

Instructional Framework and OER Integration

The undergraduate vibrations course is structured to create an integrated learning environment in which theoretical foundations, computational modeling, and hands-on experimentation reinforce one another. The course directly addresses three persistent challenges in vibrations education: limited access to laboratory infrastructure, uneven student preparation in differential equations and systems modeling, and reliance on proprietary computational software [4, 12, 30]. The instructional framework therefore adopts an open-resource, low-cost, and intentionally scaffolded structure that couples conceptual development with iterative simulation and experimental practice.

The course is anchored by a freely available OER textbook developed specifically for this curriculum. Each chapter introduces core vibration topics, including free vibration, forced response, resonance, damping, and modal behavior, using accessible notation and structured derivations [18–22]. The OER framework ensures that all students have unrestricted access to theoretical content, worked examples, and high-resolution figures without financial barriers. This approach is consistent with growing evidence that OER adoption can reduce inequities while maintaining or improving student outcomes [19–23].

Each theoretical module is supported by instructor-developed video lectures presenting worked examples and guiding students through preliminary analytical steps. These videos bridge conceptual derivations and computational modeling, enabling students to review material at their own pace outside scheduled class sessions. Prior research indicates that multimedia instruction preceding laboratory engagement supports students with uneven mathematical preparation [31–33]. Following the theoretical and video components, students engage with Mathematica notebooks and interactive Demonstrations designed to visualize and manipulate key vibration concepts. These computational tools support symbolic derivation, numerical simulation, frequency-response analysis, and parameter sweeps. Interactive modules allow students to vary stiffness, damping, mass, or forcing frequency and observe corresponding changes in amplitude, phase, stability, and transient response [24–29].

This intermediate computational stage is critical for developing physical intuition prior to formal mathematical abstraction. The modeling environment prepares students to formulate analytical predictions that are subsequently evaluated through laboratory experimentation. The overall instructional sequence reflects established practices in dynamic systems education in which conceptual visualization precedes complex derivation [7–10, 30].

Laboratory activities are intentionally implemented using affordable and widely accessible instrumentation to promote scalability and institutional adoption. The laboratory architecture integrates wireless accelerometers and force sensors selected for plug-and-play compatibility and reliable dynamic measurement, together with portable data acquisition interfaces capable of supporting both time-domain and frequency-domain analysis. Modular 3D-printed fixtures, including cantilever clamps, beam mounts, damping caps, and mass attachment brackets, maintain consistent geometry and repeatable boundary conditions. Standard mechanical components, such as aluminum beams, compact excitation motors, and interchangeable spring elements, enable rapid reconfiguration among free vibration, forced response, and multi-degree-of-freedom system configurations.

This hardware configuration provides sufficient measurement fidelity to investigate free vibration decay, harmonic excitation response, and two-mass–three-spring systems while maintaining a total implementation cost below $5,000. The resulting cost structure is comparable to, and in some cases lower than, other recently reported low-cost instructional vibration platforms [15–17].

The course follows a consistent weekly progression, as illustrated in Figure 1. This unified structure provides a coherent learning experience and aligns with documented best practices in laboratory-integrated engineering education [7–10, 31–33]. The instructional sequence begins with foundational concepts presented through OER materials and worked examples, followed by instructor-developed multimedia lectures. Students then engage in computational modeling using Mathematica notebooks and interactive Demonstrations prior to laboratory experimentation. Laboratory activities include data acquisition, signal processing, model validation, and analysis of discrepancies between theoretical predictions and measured responses. The sequence concludes with structured reflection and interpretation to reinforce model-to-experiment connections.

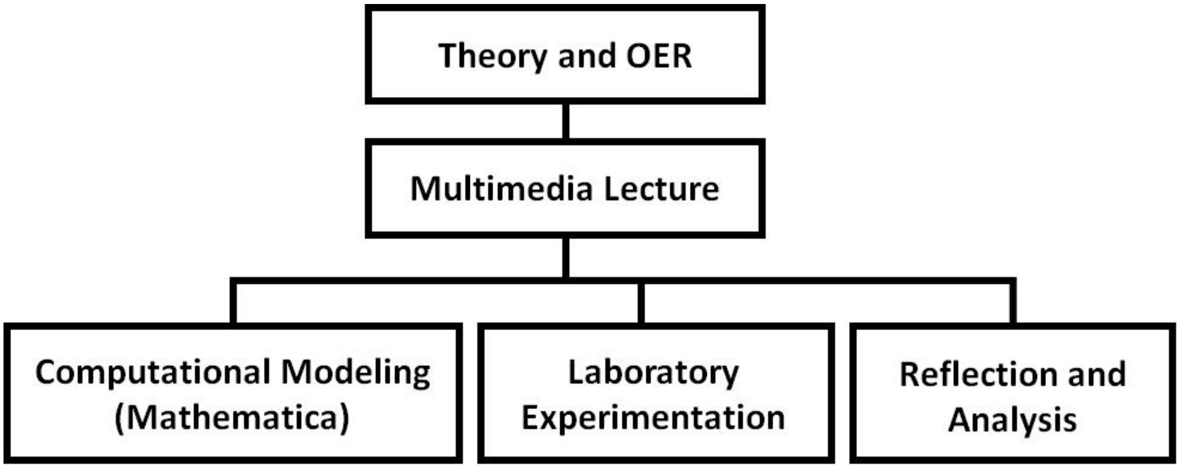

Figure 1. Structured progression of course components integrating theory, modeling, experimentation, and reflection.

Laboratory Architecture and Instrumentation

The vibrations laboratory sequence is structured around low-cost, mobile-compatible instrumentation and modular mechanical fixtures that enable investigation of canonical single- and multi-degree-of-freedom systems. Figure 2 illustrates the experimental single-degree-of-freedom mass–spring apparatus used to examine time-domain free vibration response. The system consists of a lumped mass, m (Vernier Science Education, Go Direct 250 g cart with integrated motion sensor), mounted on a low-friction dynamics track (PASCO Scientific, standard metal cart and 1.2 m dynamics track system) and connected to two linear springs, k_1 and k_2 (PASCO Scientific, dynamics track spring set). The onboard wireless motion sensor measures displacement and velocity and transmits data via Bluetooth to a portable data acquisition interface (Vernier, LabQuest 3), which can be accessed using laptops, tablets, or smartphones.

This architecture provides a mobile and accessible platform for time-domain data collection while simplifying laboratory logistics. The configuration supports rapid deployment, flexible classroom implementation, and direct alignment between the physical system and its corresponding analytical model.

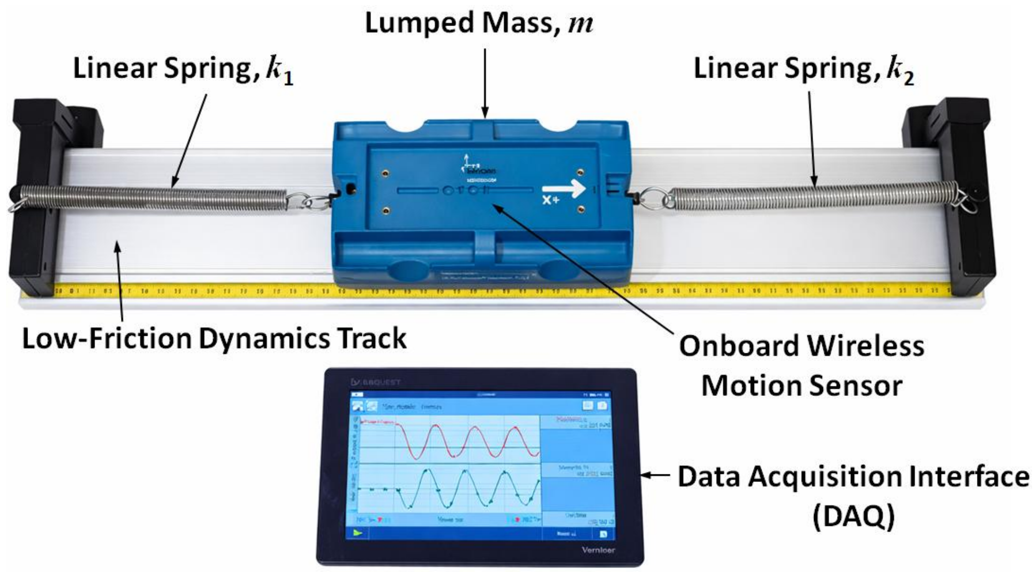

Figure 2. Experimental single-degree-of-freedom mass–spring vibration apparatus.

Beyond the single-degree-of-freedom configuration shown in Figure 2, the laboratory platform incorporates a modular instrumentation framework designed to support progressively more complex dynamic systems. Wireless cart-based motion sensors provide simultaneous measurement of position, velocity, and acceleration along a linear track, while Bluetooth-enabled data acquisition interfaces enable direct integration with laptops, tablets, and smartphones. Interchangeable masses and spring elements allow rapid reconfiguration between single- and multi-degree-of-freedom assemblies.

Additional experimental fixtures include a custom-built forced vibration apparatus for harmonic excitation studies and a vertical mass-and-springs-in-parallel assembly for stiffness characterization. Several structural components are fabricated using 3D-printed brackets and alignment guides to maintain consistent geometry and repeatable boundary conditions across student groups.

Sensor sampling rates and measurement ranges are selected to resolve key dynamic behaviors, including free decay response, resonance amplification, and modal characteristics, while remaining compatible with low-cost instructional hardware [15–17].

Laboratory Experiments and Technical Requirements

Table 1 summarizes the primary experiments included in the vibrations laboratory sequence, along with corresponding hardware requirements and targeted conceptual objectives. The experimental set is organized to establish a coherent progression from single-degree-of-freedom behavior to increasingly complex dynamic systems, while remaining fully implementable using low-cost instrumentation and modular 3D-printed fixtures.

Table 1. Experiments Developed for Undergraduate Vibrations Course

Experiment	Physical System	Instrumentation and Technical Requirements	Primary Concepts
1. Single-DOF Free Vibration	Cart attached to a single horizontal spring on a track	Vernier Go Direct cart sensor (position/acceleration), adjustable mass, known spring constant, sampling rate ≥ 100 Hz, low-friction track	Natural frequency, undamped and lightly damped free response, logarithmic decrement
2. Damped Free Vibration	Cart with added damping element (friction pad or dashpot)	Same as Exp. 1 plus damping element, ability to adjust damping level, sampling rate ≥ 100 Hz	Damping ratio, decay envelope, energy dissipation, estimation of damping coefficient
3. Two-Mass Three-Spring System	Two carts coupled by three springs on a track	Two Go Direct carts, three springs in series/parallel configuration, synchronized data collection, sampling rate ≥ 200 Hz	Coupled modes, mode shapes, natural frequencies of multi-DOF systems, modal superposition
4. Vertical Mass with Springs in Parallel	Vertical mass supported by three parallel springs	Vernier accelerometer or displacement measurement, vertical frame, known spring constants, sampling rate ≥ 100 Hz	Equivalent stiffness in parallel, free vibration in vertical DOF, stiffness identification
5. Forced Vibration of Single-DOF	Cart or mass excited by a sinusoidal forcing mechanism (custom-built motor/gear mechanism)	Go Direct sensor for displacement or acceleration, forcing device with adjustable frequency, capability to sweep frequency, sampling rate ≥ 500 Hz	Steady-state forced response, resonance, frequency response, amplitude and phase versus frequency

Wireless data acquisition interfaces and mobile-compatible instrumentation simplify experimental setup, allowing students to concentrate on physical modeling, data interpretation, and model validation rather than hardware configuration.

Integration with Computational Modeling

Prior to each laboratory session, students use Mathematica notebooks to derive or verify the governing equations of motion for the system under study, compute theoretical natural frequencies, damping ratios, and frequency-response functions, and generate predicted time histories and frequency spectra for specified system parameters.

For the externally forced spring–mass system, students solve the equations of motion, obtain analytical expressions for position and velocity response, and vary forcing frequency and system parameters to examine resonance conditions. This preparatory modeling establishes clear qualitative and quantitative expectations prior to experimentation, reducing unstructured trial-and-error and supporting deeper analysis of discrepancies between measured and predicted responses [24–29].

Assessment and Results

Assessment Methods

The study was reviewed and designated exempt educational research under institutional guidelines. A cohort of 17 students enrolled in the undergraduate vibrations course participated in the assessment.

To evaluate student performance and autonomy, several quantitative and behavioral metrics were defined and tracked throughout the semester. Behavioral measures included: (1) time to first successful measurement, defined as the elapsed time from the beginning of a laboratory session until a team obtained a valid free-vibration or forced-response dataset; (2) total laboratory completion time, defined as the duration from session start until all required measurements were completed; and (3) the number of instructor assistance requests associated with sensor configuration, data acquisition setup, or experimental troubleshooting.

Experimental accuracy was evaluated by comparing measured response quantities to theoretical predictions generated using Mathematica-based computational modeling. For each experiment, students computed theoretical values prior to laboratory implementation. Experimental measurements were obtained using onboard position sensors or direct physical measurements, depending on the configuration. Experimental quantities were reported with associated 95% confidence intervals. A one-sample *t*-test was performed to assess differences between experimental and theoretical values, with statistical significance evaluated at the $\alpha = 0.05$ level.

Learning outcomes were assessed using a rubric designed to evaluate student proficiency in experimental design and sensor configuration, data acquisition and uncertainty evaluation, time- and frequency-domain analysis, and interpretation of discrepancies between theoretical predictions and measured responses. Rubric scores were recorded on a four-point scale and compared between early- and late-semester laboratory submissions using paired t-tests.

Experimental Accuracy

Each laboratory experiment includes measurable accuracy standards aligned with established expectations in undergraduate vibrations and structural dynamics education [1–3, 7]. Table 2 summarizes the comparison between theoretical predictions and experimentally measured response quantities.

Table 2. Comparison of theoretical and experimental response quantities.

Laboratory	Theoretical Value	Experimental mean ± 95% CI	Theoretical value within 95% CI (Yes/No)
Single-mass two-spring system	$f = 13.3$ Hz	13.4 ± 0.5 Hz	Yes
Three springs in parallel with one mass	$\Delta x = 3.4$ cm	3.1 ± 0.3 cm	Yes
Two-mass three-spring system	$f_1 = 13.3$ Hz	13.4 ± 0.5 Hz	Yes
(series configuration)	$f_2 = 6.5$ Hz	6.1 ± 0.6 Hz	
Forced single-mass two-spring system	$f = 13.3$ Hz	13.6 ± 0.5 Hz	Yes

Across all laboratory configurations, the theoretical values fall within the 95% confidence intervals of the experimental measurements. No statistically significant differences were detected between theoretical and measured values at the $\alpha = 0.05$ level. These results demonstrate agreement between analytical predictions and experimental observations for all laboratory configurations evaluated.

Learning-Outcome Results

Learning outcomes were evaluated using a four-point rubric assessing student proficiency in experimental design and sensor configuration, data acquisition and uncertainty evaluation, time- and frequency-domain analysis, and interpretation of discrepancies between theoretical predictions and experimental results. Early- and late-semester rubric scores were compared using paired t-tests.

Table 3 summarizes the mean rubric scores for each category. Improvements were observed across all dimensions, with statistically significant gains ($p < 0.01$) in experimental design, data analysis, frequency-domain interpretation, and modeling and simulation. The largest increase was observed in frequency-domain interpretation, particularly in forced vibration and two-mass three-spring experiments.

Table 3. Early- and late-semester rubric scores with paired *t*-test results.

Category	Early-Semester Mean	Late-Semester Mean	Improvement	Statistical Test (paired *t*-test)
Experimental Design	2.8	3.6	+0.8	$p < 0.01$
Data Analysis	2.7	3.7	+1.0	$p < 0.01$
Frequency-Domain Interpretation	2.4	3.5	+1.1	$p < 0.01$
Modeling and Simulation	2.6	3.7	+1.1	$p < 0.01$

Behavioral Indicators of Skill Development

Behavioral indicators were tracked to evaluate changes in student autonomy and procedural fluency over the semester. Time to first successful measurement during early free-vibration laboratories ranged from approximately 45–60 minutes, whereas later laboratories required approximately 10–20 minutes to obtain a valid dataset. Total laboratory completion time decreased from the full three-hour session in early experiments to approximately 1.0–1.5 hours in later sessions.

Instructor assistance requests declined by approximately 50% by the end of the semester. The quality of pre-laboratory predictions also improved, reflected in increased accuracy of estimated natural frequencies, damping ratios, and mode shapes.

Student Feedback

End-of-semester reflections indicated that students valued the mathematical visualizations introduced prior to laboratory sessions. Many reported that the combined use of simulations and experimentation enhanced their conceptual understanding, with several noting that vibration phenomena "made sense" as physical systems for the first time. Students also highlighted that the mobile data acquisition configuration enabled experimentation outside the traditional laboratory environment, reinforcing learning through flexible application.

These qualitative responses are consistent with the quantitative improvements observed in experimental accuracy, rubric-based learning gains, and behavioral efficiency metrics.

Discussion and Implications

The assessment results indicate that the redesigned vibrations course effectively integrates theoretical instruction, computational modeling, and low-cost laboratory experimentation into a coherent and scalable undergraduate learning framework. The findings highlight several themes related to pedagogy, technical implementation, and accessibility.

Pedagogical Impact

The structured progression from theory to simulation to physical measurement supports student learning across varied levels of mathematical preparation. Students with limited backgrounds in differential equations or systems modeling appear to benefit from beginning each module with conceptual development through the OER textbook, followed by multimedia explanations and Mathematica-based simulations. This multimodal instructional sequence promotes development of physical intuition prior to formal derivation, consistent with established scaffolding strategies in engineering mechanics education [31–33].

Improvements in rubric-based laboratory scores, particularly in frequency-domain interpretation and modeling proficiency, suggest that the integration of computational modeling with hands-on experimentation strengthens students' ability to relate analytical predictions to observable physical behavior. Behavioral indicators, including reduced time to first successful measurement and fewer instructor assistance requests, further reflect gains in autonomy and procedural fluency. These outcomes are consistent with prior studies demonstrating that visualization and simulation tools can reduce cognitive load and enhance experimental preparedness [24–29].

Technical and Logistical Effectiveness

The laboratory architecture demonstrates consistent accuracy and repeatability while operating at substantially lower cost than conventional vibration laboratory systems. Wireless motion sensors integrated with portable data acquisition interfaces generate time-domain measurements suitable for extracting natural frequencies, damping ratios, and forced-response characteristics. The experimentally identified response quantities remain in agreement with theoretical predictions obtained through Mathematica-based modeling, with differences contained within expected experimental uncertainty.

The wireless data acquisition framework reduces setup complexity and supports flexible deployment using laptops, tablets, or smartphones. This portability facilitates efficient laboratory execution and enables selected activities to be conducted in nontraditional instructional spaces without compromising measurement quality. The incorporation of modular 3D-printed fixtures enhances experimental consistency by maintaining controlled boundary conditions while permitting rapid reconfiguration for multi-degree-of-freedom systems. These components are inexpensive to fabricate and straightforward to repair or modify, reinforcing the platform's scalability and long-term sustainability.

Equity and Accessibility

The outcomes of this course suggest several broader implications for engineering education. Modern instructional-grade instrumentation can provide sufficient accuracy and resolution for advanced vibration topics, including free vibration, forced response, damping estimation, and multi-degree-of-freedom behavior. These findings indicate that high-cost laboratory systems are not a prerequisite for meaningful experimental engagement with dynamic systems.

Curricula grounded in open educational resource (OER) materials enhance flexibility and replicability. Freely available textbooks, computational demonstrations, and aligned multimedia resources create a transferable instructional ecosystem that can be adopted or adapted across institutions with varying resource constraints.

Structured scaffolding remains essential for mathematical accessibility. Introducing vibratory phenomena through visualization and guided computational exploration prior to formal derivation supports students with uneven preparation in differential equations and linear systems.

Behavioral indicators, including reduced laboratory completion times and decreased reliance on instructor intervention, provide complementary evidence of skill development beyond traditional grade-based measures. These metrics capture procedural fluency and experimental confidence that may not be fully reflected in summative assessments.

Mobile-compatible data acquisition expands the range of viable instructional environments. The ability to collect experimental data using laptops or handheld devices enables flexible deployment and aligns with inclusive instructional design principles.

These implications position the course as a scalable framework for delivering laboratory-intensive vibrations instruction across institutions with diverse student populations and resource constraints.

Conclusions

This paper presents the development, implementation, and evaluation of a full-semester undergraduate vibrations course that integrates open theoretical resources, interactive computational modeling, and low-cost experimental hardware. The findings demonstrate that laboratory-intensive instruction in vibratory systems can be delivered within a constrained budget, reducing typical implementation costs from the $20,000–$40,000 range to under $5,000 while maintaining technical rigor.

The instructional framework follows a structured progression from theory to simulation to experiment, supporting students with varied mathematical preparation while fostering both conceptual understanding and practical competency. The integration of OER materials, multimedia pre-laboratory instruction, and Mathematica-based modeling promotes the development of physical intuition and computational fluency prior to hands-on experimentation. This sequence is associated with measurable improvements in experimental design, quantitative data analysis, and interpretation of frequency-domain behavior.

The laboratory platform, built around wireless motion sensing, portable data acquisition interfaces, and modular 3D-printed fixtures, provides sufficient accuracy for investigating free vibration, forced response, damping, transmissibility, and modal characteristics. The system supports efficient data collection and analysis while reducing reliance on proprietary software and specialized facilities. Behavioral evidence, including reductions in setup and laboratory completion times, further reflects increased student autonomy and proficiency in instrumentation and model-based reasoning.

The combined use of open educational resources, affordable instrumentation, and scaffolded pedagogy establishes a scalable framework for institutions seeking to strengthen vibrations instruction without substantial capital investment. Future work will expand the experimental suite to include nonlinear vibration and operational modal analysis, develop remote and hybrid laboratory modules, and examine long-term retention and transfer of learning through multi-term data collection.

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