Using Mobile Devices to Teach Structural Dynamics and Structural Health Monitoring

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Abstract

This paper studies the effect of using mobile devices to teach topics in structural dynamics and structural health monitoring (SHM). Devices, like iPods and smartphones, running apps that record accelerometer data are increasingly common in the classroom and are more available to instructors. Given that structural dynamics and SHM are commonly advanced courses or research topics, the goal of this work was to create and evaluate a module that employs increasingly commonplace mobile devices to actively engage students in these topics and to generate enthusiasm for further study in structural dynamics and structural health topics like damage detection in engineered structures. Assessment of student laboratory reports for demonstration of stated learning objectives and student survey results are presented.

Introduction

While there is plenty of discussion about technology in the classroom, exposing students to cutting edge approaches to structural health monitoring using familiar devices may have a positive influence on learning in a laboratory session. Creating laboratory procedures to simulate practical field scenarios increases the inherent connection between education and practical experience. The purpose of this paper is to document the research and analysis performed on an introductory laboratory session for structural dynamics with an emphasis on structural health monitoring. The primary research questions tested with this study are

- Do devices in the classroom foster enthusiasm for the topic?
- If devices are used by a group of students, does this have an impact on learning?
- Does the hands-on nature of the laboratory matter? Or, is data analysis and calculation sufficient? Is direct instruction even necessary?

In order to test these questions, a group at Oregon Institute of Technology prepared a laboratory module, conducted a laboratory experiment and evaluated the learning gains and perceptions of three groups of students using a performance-based survey as well as evaluation of student lab reports.

In a structural dynamics laboratory setting, three alternative delivery methods were used as a basis for the study. The students were divided into three groups prior to participating in the laboratory experiment. The first group consisted of graduate students in a hands-on laboratory setting (the “Experiment” group). The second group consisted of undergraduate students in a purely computational laboratory (the “No experiment” group), using the data collected from the hands-on laboratory to complete the analysis portion of the assignment. Finally, the third group consisted of senior and graduate students who had traveled to Washington D.C. for the Transportation Research Board (TRB) convention during the assigned laboratory session. This third group of students (the “No lab” group) received only the data collected and a description of the laboratory, simulating an online course delivery style.

This paper provides a summary of current studies and observations directly corresponding to the research questions outlined above, an in-depth description of the laboratory module development, specific conduct of each laboratory section, a summary of the laboratory experiment procedure, and results of the assessments utilized with a discussion of implications. The laboratory module effectively follows Feisel and Rosa's Fundamental Objectives of Engineering Instructional Laboratories for the "Experiment" group, but provides less emphasis on senses in the "No experiment" and "No lab" versions[2]. The materials, handouts, and instruction for each laboratory session are located in the corresponding appendices. In assessing student responses in each laboratory section, the researchers analyzed survey responses and manually assessed the written responses for demonstration of learning objectives. Following the laboratory development and conduct and analysis of survey results, this paper will discuss the conclusions gathered from this study with respect to the research questions above.

According to recent research in alternative teaching and learning practices in science and engineering courses, students seem to respond more positively to inductive or active learning when compared with traditional lecture sessions[6]. The purpose of this study is to evaluate the effect of mobile devices as experimental tools in an active learning environment for courses in structural dynamics and structural health monitoring. In the context of this study, alternative teaching practices refer to non-traditional methods of instruction, including active, inductive, and problem based learning (PBL). In this study, the use of mobile devices in the classroom was intended for the purposes of data collection and clarifying the quantities measured. Active learning with the use of personal mobile devices is a relatively modern and sometimes controversial topic that often receives outstanding support or determined opposition in the field of engineering and related fields.

The wide use and acceptance of technology in the classroom provides an opportunity for students to interact more efficiently with information and peers in a learning environment. The interactive teaching methods discussed in this paper relate to active, inductive, and problem based learning (PBL). Active learning is most generally defined as any instructional method of engaging students for the entire duration of the teaching contact time[6]. In addition to traditional homework and examination, active learning allows students to participate in collaborative activities that positively influence student attitudes and study habits for course material[6]. Inductive learning encompasses interactive instruction techniques including inquiry learning, PBL, project-based learning, case-based teaching, and discovery learning[5]. Problem based learning (PBL) incorporates relevant problems introduced at the beginning of instruction to provide context and motivation for the learning that remains[6]. In response to recent research involving the introduction and use of alternative learning in the classroom, studies suggest that "students will retain information longer and perhaps develop enhanced critical thinking and problem-solving skills," if active learning methods are employed[6].

The use of devices in the classroom affects the perception of material by using relatable and convenient tools in a practical application. When used as a tool for active learning, such as data collection and analysis, rather than for low level communication or recording, mobile device technology has the ability to foster the amplification, extension, reconstruction, and reorganization of knowledge in an interactive learning environment[3]. Using devices in an active learning environment encourages a greater level of critical thinking and problem solving that supports good practice in engineering laboratories[2,3].

Precise data collection in the engineering field requires reliable and consistent results available in a laboratory, as well as in field scenarios. Utilizing mobile devices and smartphones to collect and measure data encourages students to experience the reality of engineering measurement with the ease of convenient collection technology. Although the utilization of smartphone data collection is a relatively recent concept for structural dynamics and structural health monitoring, mobile devices have been and are currently in use as monitoring systems for transportation structures[4]. Researchers from Nokia Research Center Palo Alto, Navteq, and UC Berkeley conducted an experiment known as Mobile Millennium, involving the implementation of a state-of-the-art mobile phone GPS data collection system to monitor traffic conditions and real-time traffic estimation[8]. Following the experiment, researchers found that developing this mobile application would allow for the successful collection, analysis, and reporting of traffic condition estimates[8]. As in the use of GPS data for traffic condition estimation, the accelerometer component and iSeismometer application provided in modern mobile devices have significant potential for damage detection and estimation of structural health in the field of structural engineering.

Module Development

Drawing from concepts in structural dynamics and structural health monitoring, the structural engineering instructor and two graduate students in the civil engineering program determined an appropriate laboratory for this study, based on several key components. In producing this laboratory experiment, the researchers discussed experimental ideas that would encourage students to recognize and utilize concepts previously taught and apply that knowledge to the dynamic behavior of bridges specifically. Using concepts of free vibration and damage detection using dynamic parameters of bridge structures, the researchers consulted resources such as the first two chapters in Chopra's *Dynamics of Structures* and Helmut Wenzel's *Health Monitoring of Bridges*, to develop an introductory laboratory that would provide a challenging yet attainable procedure for a three-hour laboratory period[1,7]. An ideal laboratory, as concluded by the researchers, would provide for a practical field scenario alternative, while incorporating assessment through laboratory experimentation. Following development of the framework of the laboratory and testing of various beam configurations, a cantilever beam was chosen for the configuration, as depicted in the corresponding sections below.

Dividing the students into three groups allowed for the analysis of student perceptions as a result of an active learning technique, computation-only environment, or an online course-based delivery style. In order to assess and examine the performance criteria pertinent for the given research objectives, the researchers defined the laboratory report requirements and developed a group-specific survey. These chosen criteria were based on the most relevant aspects of this laboratory experiment: the study of devices used as a data collection tools and alternative teaching techniques for each section.

After students completed the laboratory report and survey, the results were evaluated and analyzed by the researchers. These responses were analyzed and reported in the paper based on average ratings specific to each section. Using the submitted reports and surveys, the researchers assessed performance ratings from students to attempt to answer the research questions outlined above.

Conduct of the Laboratory Sections

The 19-student class was broken into three sections. The two students involved in developing the module participated in different sections, but did not take the assessment survey and are not included in the results.

For the two in-lab sections, the laboratory period began with an orientation to the topic and review of the laboratory handout (see Appendix) and procedure. The following learning objectives were used to structure the delivery and evaluate learning:

1. *Identify the natural frequency and period of a freely vibrating single degree-of-freedom (SDF) system using*
    a. *Measurement of free vibration with an initial displacement*
    b. *Calculation with system stiffness and mass parameters*
2. *Identify the damping ratio of a freely vibrating SDF system by supplying an initial displacement and analyzing the log decrement of the measured response*
3. *Describe the effect of mass and stiffness on the natural frequency and natural period of a SDF system*
4. *Describe the parameters that affect the damping ratio of a structure*
5. *Analyze dynamic response data to determine the natural period and damping ratio of a structure*
6. *Evaluate the ability of multiple dynamic evaluations to identify damage in a structure*

The laboratory sections consisted of the following groups:

1. "No experiment" – The group of seven students who attended the laboratory and participated in the pre-lab lecture and in-lab data analysis, but did not conduct the experiment. These students did not touch the experimental apparatus physically and encountered it only as a 2D drawing and verbal description.
2. "Experiment" – The group of seven students who attended the laboratory, participated in the pre-lab lecture, physically tested the tip-loaded cantilever, and conducted in-lab data analysis. These students participated in the complete experience.
3. "No lab" – The group of three students who were not able to attend the laboratory and completed it using the materials provided electronically along with a short description of what they missed in the laboratory and details involved in the data analysis. These students had an experience similar to online instruction. No video of the professor nor photographs of the apparatus were provided.

Laboratory Experiment

The laboratory experiment, conducted by the "Experiment" students, employed an eight-foot Douglas Fir Larch Standard grade 2x4, set up as a four-foot long cantilever beam. It was clamped to a testing frame with C-clamps and oriented to bend about the minor axis (Figure 1). On the free end, a 20-lb weight was hung to serve as a concentrated mass. An iPod loaded with the iSeismometer app was placed on top of the free end to collect acceleration response data. Due to the relatively long period and low frequency of the beam in this configuration, there was no need to clamp the iPod to the member to ensure good test data. Once the test was properly set up, the beam was displaced by hand at the free end and allowed to oscillate while acceleration response data was collected in the Z (vertical) axis.

(a)

(b)

Figure 1. Test configuration (a) and 50% section loss in the beam (b).

Three test scenarios were conducted, with different amounts of section loss inflicted using a circular saw, to simulate long term damage to the beam: one with the full section, one with 25% damage, and one with 50% damage (Figure 1b).

After each test was complete, the raw data was exported directly to an Excel spreadsheet by the iSeismometer app. Acceleration data was plotted with respect to time and used to find the natural period and damping ratio of the system. From the natural period other dynamic parameters were calculated, including circular and cyclic natural frequency.

The dynamic parameters of natural period and damping ratio were plotted against the percent section loss of the member, and students were asked if they could identify any correlation between the damage induced in the beam and its dynamic response.

As part of the exercise, students were asked to confirm the physical properties of the beam that and use them in subsequent calculations before beginning the test. These values were used to calculate the stiffness of the beam and confirm analytically that the natural period of the system, measured by experimentation, was correct.

Assessment

Assessment of learning was based on (1) instructor evaluation of student laboratory memoranda following the laboratory and (2) student perception of learning gains (via survey). Each assessment was conducted according to the learning objectives stated in the Conduct of the Laboratory Sections section above and repeated here for convenience.

1. Identify the natural frequency and period of a freely vibrating single degree-of-freedom (SDF) system using

a. Measurement of free vibration with an initial displacement

b. Calculation with system stiffness and mass parameters

2. Identify the damping ratio of a freely vibrating SDF system by supplying an initial displacement and analyzing the log decrement of the measured response

3. Describe the effect of mass and stiffness on the natural frequency and natural period of a SDF system

4. Describe the parameters that affect the damping ratio of a structure

5. Analyze dynamic response data to determine the natural period and damping ratio of a structure

6. Evaluate the ability of multiple dynamic evaluations to identify damage in a structure

Instructor Evaluation of Student Laboratory Memoranda

Levels of achievement for each learning objective were used for grading the memorandum format reports submitted by students. Each learning objective was scored on a scale from high (4) to low (2) proficiency, with the absence of demonstration scored lowest (1) (Figure 2).

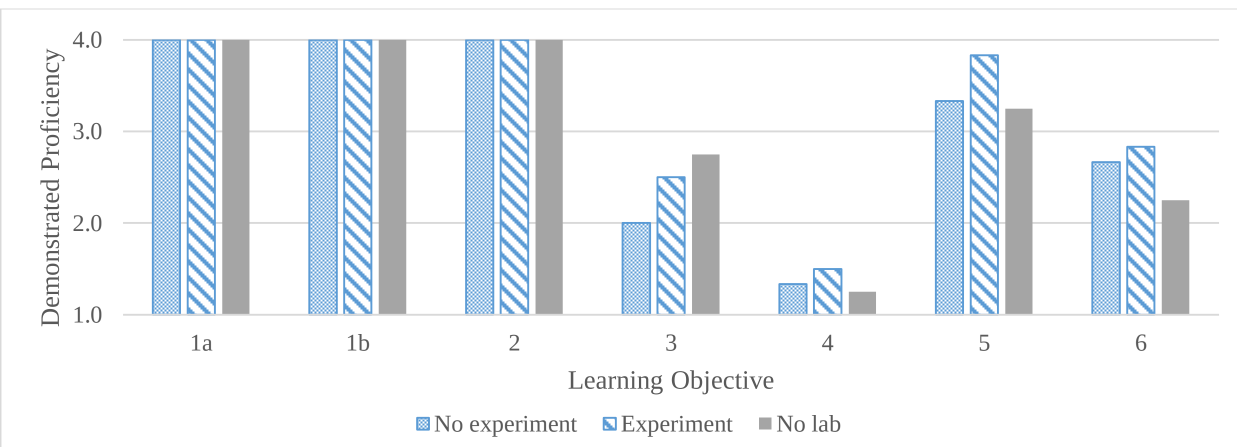

Figure 2. Average demonstrated proficiency per learning objective for each lab section.

The first two learning objectives were essentially completed during the laboratory and available for checking by the instructor. All students included the results in their report.

Scoring of the last four learning objectives was based on written descriptions provided by the students. Without more students in each section, these results do not provide conclusive evidence that the laboratory section influenced the student proficiency as demonstrated by their report.

Variations appeared to be correlated more with a given student's usual degree of effort on assignments like this than their understanding. Stated differently, some students did not write enough to evaluate their understanding of the learning objectives.

While many students noted that increases in natural period were demonstrated due to reduced stiffness resulting from the inflicted damage, not all of them clearly articulated this conclusion. Damping ratio was more variable and results depended on the values students selected to calculate the damping ratio. Most students attributed this variability to error and declined to comment further on the expected trend. However, all students concluded that the damping ratio is less influenced by damage than the natural period.

There was wide variability in the responses based on learning objective six (*Evaluate the ability of multiple dynamic evaluations to identify damage in a structure)*. Regardless of graduate or undergraduate student status, some students used the opportunity to explore, deeply in some cases, the challenges and potential benefits of structural health evaluation using dynamic properties, while others indicated that the challenges were likely too great and the problem was essentially intractable. It was these latter students who wrote the least.

Student Perception of Learning Gains, Use of Technology, and Conduct of Laboratory

After completing their laboratory reports, students participated in a survey and rated their ability to do the things indicated in each learning objective on a 4-point scale from "poor (1)" to "fair (2)" to "good (3)" to "excellent (4)". "Not sure" was also included as an option but was not selected by any student. Student self-reported abilities to do what is described in the learning objectives before and after the laboratory are provided per group in figures 3 (No experiment), 4 (Experiment) and 5 (No lab). In general, the "No experiment" section indicated that they had greater proficiency in the learning objectives initially. Learning gains are shown in Figure 6.

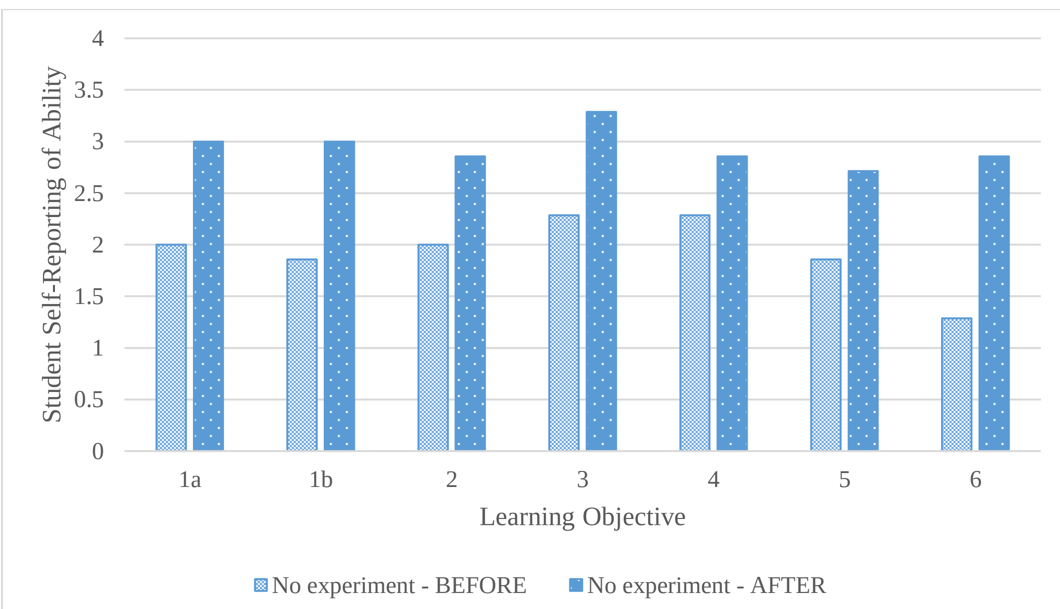

Figure 3. Self-reported abilities of students for each learning objective before and after the "No experiment" laboratory section.

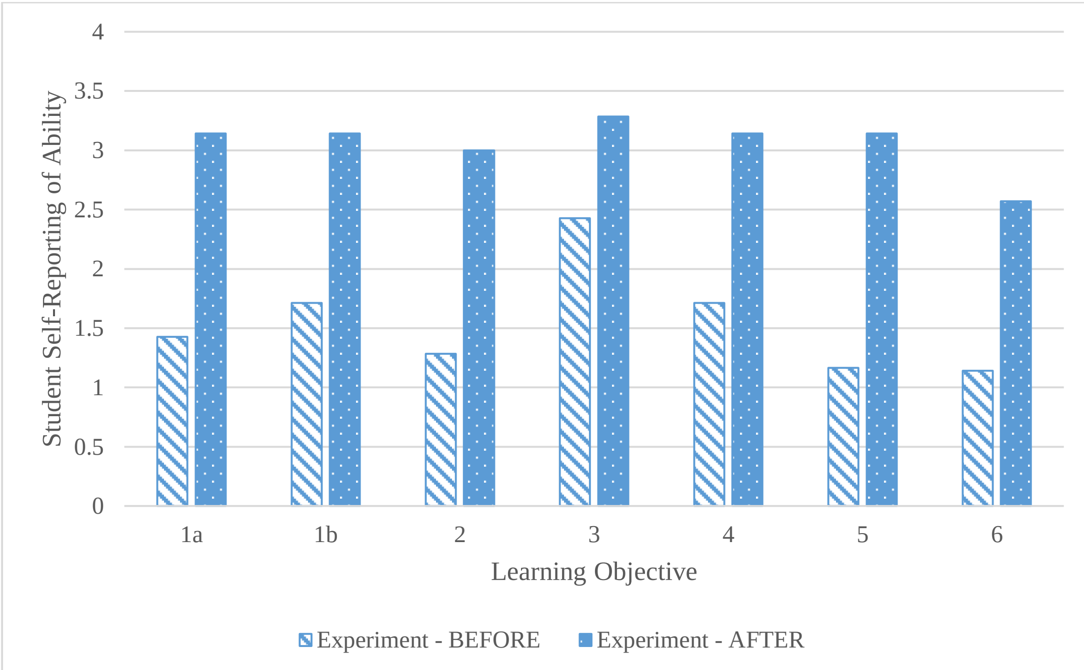

Figure 4. Self-reported abilities of students for each learning objective before and after the "Experiment" laboratory section.

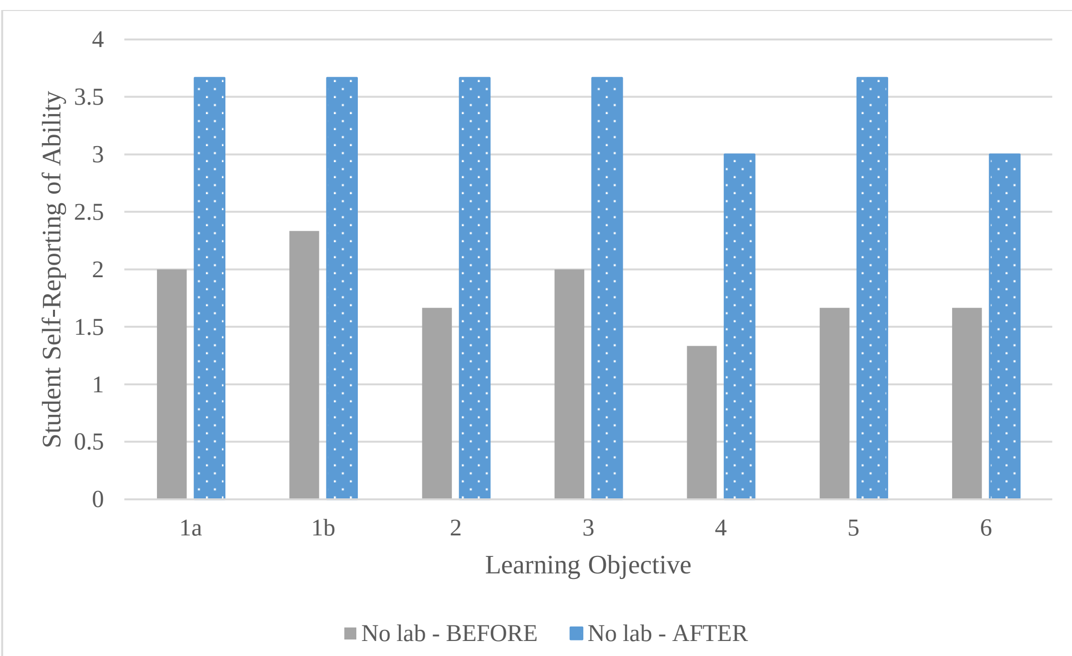

Figure 5. Self-reported abilities of students for each learning objective before and after the "No lab" laboratory section.

The average learning gain for each laboratory section is summarized in figure 6. The total average learning gain reported by the No experiment" section was 1.00, while the average learning gain reported by the "Experiment" section was 1.53 and 1.67 for the "No lab" section. Students in the "Experiment" section self-reported greater learning gains for each learning objective except (3) *Describe the effect of mass and stiffness on the natural frequency and natural period of a SDF system* and (6) *Evaluate the ability of multiple dynamic evaluations to identify damage in a structure*. This may be the result of more discussion of this topic in the "No experiment" section. This discussion was prompted by student questions, likely as a result of not having a physical experiment to review. However, this discussion may have contributed to greater actual or perceived gains by the "No experiment" group. The greater differences in learning gains for the "Experiment" and "No experiment" sections for the other learning objectives provide some evidence that the hands-on, experimental approach was more effective.

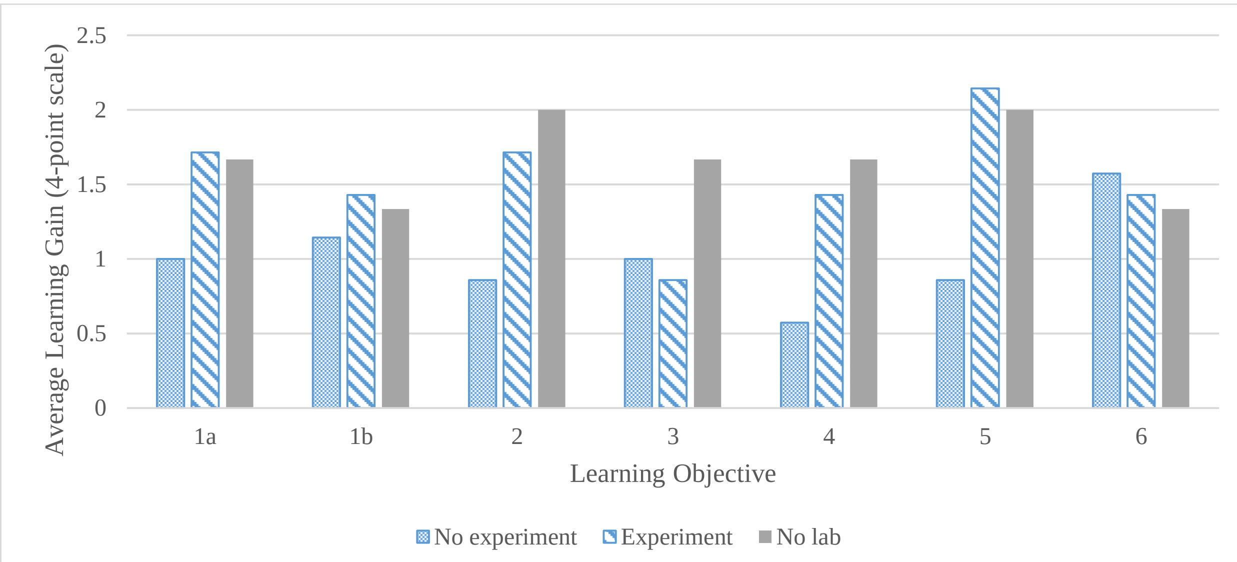

Figure 6. Average learning gain for each learning objective per laboratory section.

Given the small sample size of the "No lab" group (only three students), it is inappropriate to draw strong conclusions from these results. However, because the learning gains reported by these students are similar to the "Experiment" group, these data indicate that perhaps the learning gains made by students in an online learning environment may approach those of students in a hands-on laboratory experience. The "No lab" students reported a greater ability than the other students to perform the learning objectives for every objective except (4) *Describe the parameters that affect the damping ratio of a structure*, which is expected because there was no content in the materials supplied to these students that addressed this aspect of dynamic response. This learning objective was addressed entirely during laboratory discussion in the other sections.

Student ratings of the learning experience, technology, instructor and facilities are provided in Figure 7. These ratings are most interesting because the "No lab" section that received the least interpersonal, least physical, and least direct instruction, rated all categories the highest. The "Experiment" students rated the learning experience slightly lower than the "No experiment" students, while the technology was rated similarly, perhaps indicating that the challenges overcome during the actual conduct of the experiment by the “Experiment” students were not perceived as valuable, while the “No experiment” students had the benefit of reviewing data that had already been collected and were not exposed to the challenges of that data collection.

The students participating in the “No Experiment” section reported nearly unanimously regarding the “Least Effective” portion of the laboratory. In summarization of the comments received, the students felt that participating in the setup, conduct, and data collection would have significantly increased the overall effect of the laboratory focus on real-world bridge evaluation. As perceived by several students in the “No Experiment” and “No Lab” sections, engineering students feel hindered by the lack of connection to field or practical experience. In the “Experiment” section, students responding to the “Least Effective” survey question were primarily concerned with time constraints and the lack of pertinent dynamics or vibrations knowledge prior to the laboratory session.

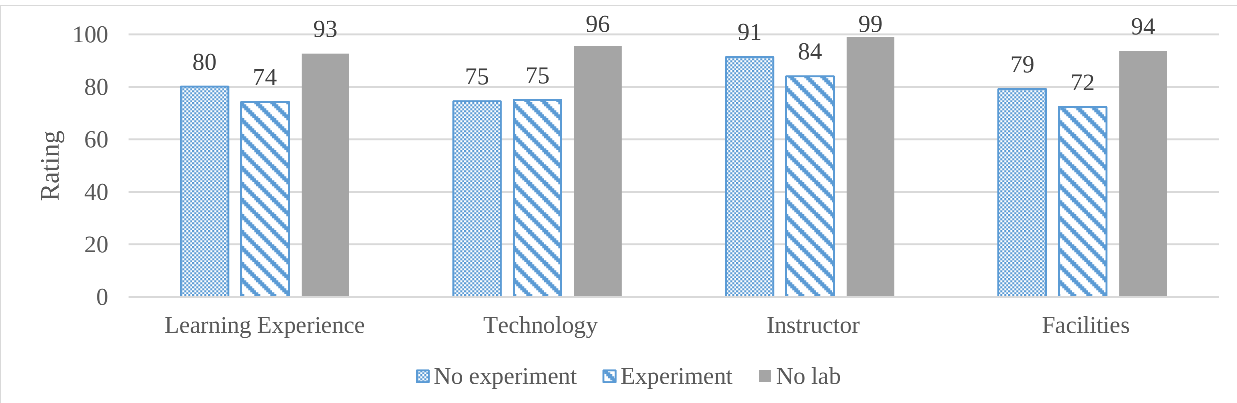

Figure 7. Average rating of learning experience, technology, instructor and facilities by the three laboratory sections (No experiment, Experiment, and No lab).

Students were nearly unanimous in their survey responses that the use of devices like the iPod for taking relevant measurements in the laboratory was valuable. This response was independent of the laboratory section and whether students had actually used the device. Specifically, when asked if the use of the iPod in this particular lab made it worse (1), the same (2), or better (3), all students indicated the same or better, with more responses indicating better (Figure 8). The use of devices like the iPod in laboratories in general received similar responses. Students also indicated that it would be even better if they were able to use their own device to conduct laboratory experiments.

Students comments further supported the conclusion that devices used in the classroom in this way are beneficial. When describing the “Most Effective” aspects of the learning environment, one student in the “No Experiment” section described the use of mobile devices as, “Using phones as equipment is effective in making the work feel more within my own reach.” Just knowing that it was a mobile device that collected the data made the material more accessible to this student.

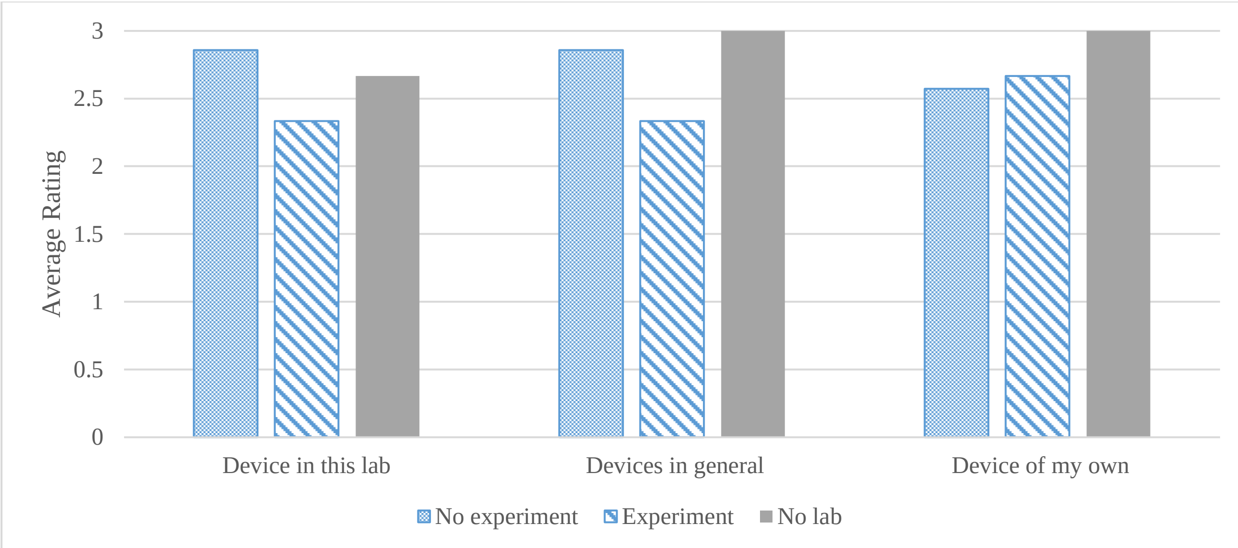

Figure 8. Student responses regarding the value of devices compared to a traditional lab – device made it or would make it worse (1), the same (2), or better (3).

Students were asked about their comfort repeating a similar experiment and analysis in a laboratory and field setting (Figure 9). Students in the “Experiment” group indicated they would be more comfortable than the “No experiment” group in a lab setting but also indicated they would be less comfortable in a field setting, perhaps because they were more aware of the complicating factors. Many of the “Experiment” students indicated in their laboratory reports more nuanced challenges that one might face in a field setting, perhaps because of their more complete experience setting up and managing the experiment and data collection. The confidence expressed by the “No lab” students may be attributed to “ignorance-as-bliss.” Without a detailed description of challenges or a hands-on experience, they may think the process is easier to replicate than those students who actually conducted the experiment or heard the instructor describe the challenges one might face in the field.

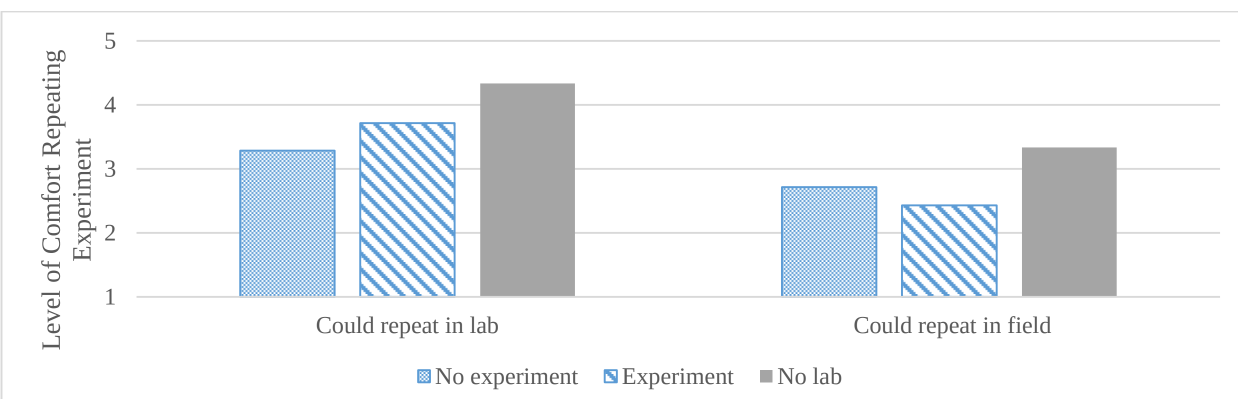

Figure 9. Student self-reported comfort repeating the laboratory procedure in lab and field scenarios (1=Not comfortable, 2=Somewhat comfortable, 3=Somewhat comfortable, 4=Comfortable, 5=Very comfortable).

Finally, a rigorous analysis of the data was conducted. Because of the low number of participants, non-parametric statistics were employed to compare the three groups. Students' rankings were summed across all learning objectives and compared between groups using Kruskal-Wallis tests. These tests revealed no significant differences between three groups before the experiment ($H(2) = 0.957$, $p = 0.617$) or after the experiment ($H(2) = 4.867$, $p = 0.082$), though the differences in post-experiment rankings did approach significance. The learning gains—the differences between the rankings after and before the experiment—were also compared and revealed no significant difference ($H(2) = 3.036$, $p = 0.215$). The proficiencies on the lab memos, as graded by the instructor, were also not significantly different ($H(2) = 0.827$, $p = 0.654$).

Further investigations did reveal one significant result. Specifically, there were significant differences in the learning gains for Objective 4 ($H(2) = 6.181$, $p < 0.025$). It was presumed that a deeper analysis of these data would suggest that the "Experiment" group had performed better than the "No Experiment" group. After using a Bonferroni correction and thus reducing alpha to 0.025 for both tests, a one-tailed Mann-Whitney test did show that the "Experiment" group had significantly higher learning gains ($Zu = 2.289$, $p < 0.025$) when asked to rate their ability to "Describe the parameters that affect the damping ratio of a structures." This may be due to the "Experiment" group's experience with the physical system, which allowed them to observe the damping of oscillations in real time rather than solely in plotted data.

Conclusion

Overall, the student response to this laboratory was positive and the demonstration of learning gains was both perceptible by the students through self-reporting and demonstrated by the students in their laboratory report submission. As an introductory module, the laboratory experiment has the benefit of simulating a significant real-world problem (structural deterioration and damage detection) as well as providing a platform for comparing theoretical and experimental results.

The primary goal in conducting this laboratory research study was to address the research questions described in the Introduction section above. According to the laboratory report submissions and survey results, students overwhelmingly agreed that experiencing a certain degree of active learning is valuable in the connection of laboratory experimentation with real-world practical scenarios. Using devices in the classroom, while not identified as significant, appears to provide a beneficial connection that makes engineering principles more accessible, based on student survey comments. Based on this feedback, mobile devices in the classroom seem to foster enthusiasm for the topic.

In the process of completing this laboratory, several students reported a more enjoyable laboratory experience as a direct result of collaboration and teamwork. For example, a student in the "Experiment" section stated that "discussing the results as a group was more valuable to me than trying to muddle through the analysis on my own," when asked about the most effective aspect of the laboratory experiment. The learning gains reported by the "Experiment" section were more than 50% greater than the "No experiment" section and student comments indicated that experiencing the laboratory demonstration either provided or would provide a much more valuable learning experience, when compared to online delivery or computation-only section. The “No lab” section simulating the online delivery mode reported the highest learning gains, but did not have the challenge that the “No experiment” students did, namely analyzing data for an experiment they did not conduct, but with the experimental apparatus available nearby. Although the online (“No lab”) group reported a relatively high degree of satisfaction without participating in the demonstration, the comments received from these students reveal a certain sense of hindrance with respect to understanding the overall intention and connection of this experiment to structural health monitoring.

As a result of this research into the effect of alternative learning techniques and device utilization in the classroom, the data observed and recorded reveal a positive connection between participation in an active learning environment, laboratory performance, and enthusiasm for the topic. Engineering students in the study prefer participating in a hands-on experiment that encourages the connection between theoretical and practical experiences, with the additional benefit of utilizing personal mobile devices for data collection to facilitate damage detection.

Following the completion of this laboratory in three alternative learning environments, further research will be conducted regarding using mobile devices to teach structural dynamics and structural health monitoring. Subsequent research will also focus on the practical application of mobile devices in field scenarios and the ability to utilize mobile device data collection for damage detection in structural health monitoring.

The use of devices was widely regarded as a positive aspect of this laboratory. As a result of this study, the instructor will continue developing laboratories that employ mobile devices like smartphones and iPods to gather data. Students expressed interest in exploring their curiosities using the devices as a result of learning about the capability of their devices. While it seems logical that greater learning can result from asking questions and having good tools with which to measure, students may not be aware of the power of the devices they have in their pockets.

Acknowledgements

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Appendix

Laboratory Handout

CE449/549 Bridge Design

Bridge Dynamics Laboratory: Natural Frequency, Damping, and Damage Detection

Learning Objectives – After completing this laboratory you should be able to

1. Identify the natural frequency and period of a freely vibrating single degree-of-freedom (SDF) system using
   a. Measurement of free vibration with an initial displacement
   b. Calculation with system stiffness and mass parameters
2. Identify the damping ratio of a freely vibrating SDF system by supplying an initial displacement and analyzing the log decrement of the measured response
3. Describe the effect of mass and stiffness on the natural frequency and natural period of a SDF system
4. Describe the parameters that affect the damping ratio of a structure
5. Analyze dynamic response data to determine the natural period and damping ratio of a structure
6. Evaluate the ability of multiple dynamic evaluations to identify damage in a structure

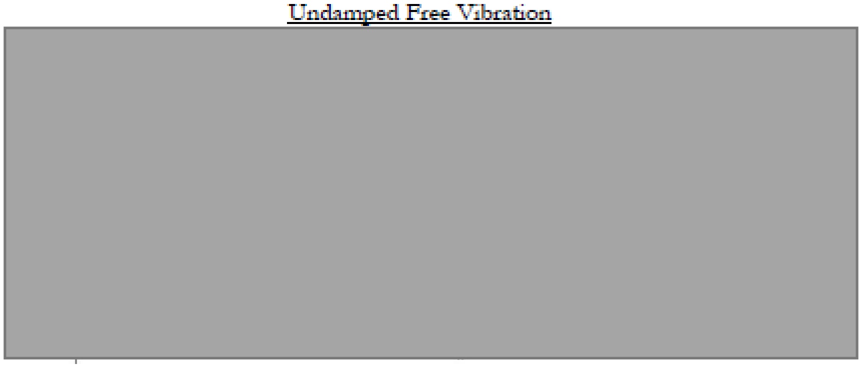
Reading

- Chopra, Chapter 1 – Equations of Motion, Problem Statements, and Solution Methods
- Chopra, Chapter 2 – Free Vibration

Symbol	Description	Units
ζ	*Damping ratio*	-
f_n	*Cyclic natural frequency (undamped)*	*Hz*
u_0	*Initial Displacement*	*in*
u_i	*Displacement at i'th peak; displacement at time i*	*in*
$\dot{u}_i$	*Velocity at time i*	*in/sec*
$\ddot{u}_i$	*Acceleration at i'th peak; acceleration at time i*	*in/sec²*
ω_D	*Circular natural frequency (damped)*	*rad/sec*
ω_n	*Circular natural frequency (damped)*	*rad/sec*
c	*Damping coefficient*	
k	*Stiffness or spring constant*	*lb/in*
m	*Mass*	*(lb-s²)/ft*
$p(t)$	*External force*	*lb*
t	*Time*	*sec*
T_D	*Natural period (damped)*	*sec*
T_n	*Natural period (undamped)*	*sec*
ρ	*Beam-to-stiffness ratio*	-

Key Formulas and Figures

Undamped Free Vibration

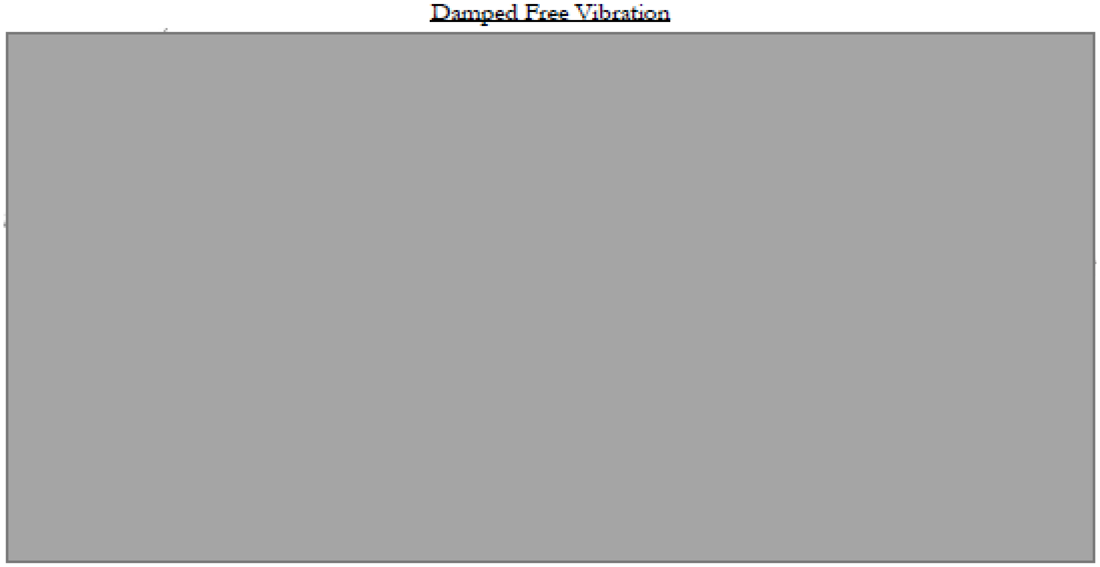


$m\ddot{u} + ku = 0$ for undamped free vibration with the solution $u(t) = u_0 cos\omega_n t + \frac{\dot{u}_0}{\omega_n} sin\omega_n t$

$\omega_n = \sqrt{\frac{k}{m}}$ is the circular natural frequency (rad/s) and $T_n = \frac{1}{f_n} = \frac{2\pi}{\omega_n}$ is the natural period (s)

$f_n = \frac{\omega_n}{2\pi}$ relates the cyclic natural frequency (Hz) to the circular natural frequency (rad/s)

Damped Free Vibration



$m\ddot{u} + c\dot{u} + ku = 0$ for damped free vibration with underdamped solution

$$u(t) = e^{-\zeta\omega_n t}[u_0 cos\omega_D t] + \frac{\dot{u}_0 + \zeta\omega_n u_0}{\omega_D} sin\omega_D t$$

Where the natural frequency of damped vibration $\omega_D = \omega_n\sqrt{1-\zeta^2}$ and damping ratio $\zeta = \frac{c}{2m\omega_n}$

The damping ratio can be measured experimentally by examining the logarithmic decrement:

$\delta = ln\frac{u_i}{u_{i+1}} = \frac{2\pi\zeta}{\sqrt{1-\zeta^2}}$ where u_i and u_{i+1} are successive peak values of displacement

$\zeta = \frac{1}{2\pi j} ln\frac{u_i}{u_{i+j}}$ evaluated over *j* cycles

Part 1 – Experimental Evaluation

1. Set up a cantilever timber beam of known stiffness with C-clamps on the structural lab frame and attach an iPod or smart phone loaded with the iSeismometer app at the tip of the span. Be careful to protect your screen but maintain access to the play/pause button on the app.
2. Determine accurate measurements for unit weight (lb/in), effective cantilever length (in), dimensions of the beam (in), elastic modulus, and moment of inertia for your beam.
3. Start the iSeismometer app recording acceleration data and immediately pluck the beam to excite the first mode of vibration.
4. Once a sufficient number of oscillations have been recorded, stop the recording and email the data to yourself for distribution to your colleagues.
5. Use the data to calculate the natural frequency, period and damping ratio of the model.

Part 2 – Analytical Evaluation

1. Prepare clear figures describing the geometry of each of the experiments you have conducted including the location of phones and additional weights. Measure the weight of the device you used to measure response. Measure cross section dimensions and calculate necessary properties. Estimate material properties for the cantilever element.
2. Use the procedures outlined in Chopra Chapters 1 and 2 and the spreadsheet available on Blackboard to calculate the theoretical natural frequency, period and damping ratio of the different structures you tested.

Part 3 – Damage Detection

1. Using the same span and beam you used in parts 1 and 2, inflict approximately 25% section loss in the bottom chord of the beam and repeat the measurement and calculation of natural frequency, period and damping ratio.
2. Using the provided circular saw, adjust the cutting depth to allow for a 25% section loss with a measuring tape. Following your cut, record the actual depth with a caliper depth gauge.
3. Repeat this process for 50% section loss, by adjusting the circular saw blade and repeating the cut to provide a greater depth in the previous cut.
4. Analyze the resulting data and indicate your ability to measure section loss with these results.
5. Discuss potential benefits and challenges to using this process in a field scenario.

Submission – Hard copy due Wednesday by 5pm next week

Prepare a technical memorandum that summarizes your procedure, and presents your results and conclusions. Were you able to successfully conduct the experiment? Answer 4 and 5 from Part 3 thoroughly. Address any sources of error or uncertainty. Attach well-formatted results to your memorandum to support your commentary.

Survey

Thank you for completing this survey regarding the Bridge Dynamics Laboratory: Natural Frequency, Damping, and Damage Detection, conducted during week 2 of Winter term in CE449/CE549 Bridge Design.

In which laboratory section did you participate?

- ○ CE549, Monday afternoon
- ○ CE449, Thursday afternoon
- ○ None, I was travelling to TRB.

BEFORE participating in the lab last week, describe your ability to do the following things?

	Poor	Fair	Good	Excellent	Not sure
Identify the natural frequency and period of a freely vibrating single degree-of-freedom (SDF) system using measurement of free vibration with an initial displacement	○	○	○	○	○
Identify the natural frequency and period of a freely vibrating single degree-of-freedom (SDF) system using calculation with system stiffness and mass parameters	○	○	○	○	○
Identify the damping ratio of a freely vibrating SDF system by supplying an initial displacement and analyzing the log decrement of the measured response	○	○	○	○	○
Describe the effect of mass and stiffness on the natural frequency and natural period of a SDF system	○	○	○	○	○
Describe the parameters that affect the damping ratio of a structure	○	○	○	○	○
Analyze dynamic response data to determine the natural period and damping ratio of a structure	○	○	○	○	○
Evaluate the ability of multiple dynamic evaluations to identify damage in a structure	○	○	○	○	○

AFTER participating in the lab last week, describe your ability to do the following things?

	Poor	Fair	Good	Excellent	Not sure
Identify the natural frequency and period of a freely vibrating single degree-of-freedom (SDF) system using measurement of free vibration with an initial displacement					
Identify the natural frequency and period of a freely vibrating single degree-of-freedom (SDF) system using calculation with system stiffness and mass parameters					
Identify the damping ratio of a freely vibrating SDF system by supplying an initial displacement and analyzing the log decrement of the measured response					
Describe the effect of mass and stiffness on the natural frequency and natural period of a SDF system					
Describe the parameters that affect the damping ratio of a structure					
Analyze dynamic response data to determine the natural period and damping ratio of a structure					
Evaluate the ability of multiple dynamic evaluations to identify damage in a structure					

With 0=low and 100=high, please rate the overall effectiveness of the

	0	10	20	30	40	50	60	70	80	90	100
Learning Experience											
Technology											
Instructor											
Facilities											

Regarding the use of an iPhone running the iSeismometer app to collect data, answer the following.

	Worse than a typical lab	Same as a typical lab	Better than a typical lab
The use of the iPhone to collect data made this lab	○	○	○
The use of devices like an iPhone make labs	○	○	○
If I had my own device to work with it would have been	○	○	○

With little or no prior exposure to structural dynamics, how comfortable would you feel in repeating this procedure in

	Not at all comfortable	Somewhat uncomfortable	Somewhat comfortable	Comfortable	Very Comfortable
a similar laboratory experiment?	○	○	○	○	○
a practical/field situation?	○	○	○	○	○
Click to write Statement 3	○	○	○	○	○

Please list and explain the things you found MOST EFFECTIVE about the learning experience.

Please list and explain the things you found LEAST EFFECTIVE about the learning experience.

Please list and explain the things you found MOST EFFECTIVE about the instructor.

Please list and explain the things you found LEAST EFFECTIVE about the instructor.

Please list and explain any concrete suggestions for improving your learning in this particular laboratory.

Student Written Responses to Survey Questions

Please list and explain the things you found MOST EFFECTIVE about the learning experience.

Experiment
Text Response
This lab put into perspective the effect damage has on structural members. We were able to see the decrease in strength of the 2"x4" member, and this enlightened me. I was able to envision processes of rusting, and how it can brutally take away from the strength of a steel member.
I liked being able to go into the lab and collect data, and then go back into the traffic lab to analyze the collected data. It gave me a better understanding of how the data is collected, and what it means, rather than just being given a set of numbers.
Actually going through the analysis process helped me understand what was going on better than the initial verbal description. Also discussing the results as a group was more valuable to me than trying to muddle through the analysis on my own.
The hands-on data collection.
Getting the data to work with via the seismometer.
No experiment
Text Response
I could picture the experiment and the concept was intriguing to me. I like participating in research.
Equations
We learned the equations and mechanics behind the excel spreadsheet and the graphs it generates. We saw the motion of the beam and the natural frequency it has, as well as the changes in the beams properties as it experienced damage.
Unique-- felt like I was participating in something that mattered--- felt like my work had more consequence than a typical lab, making work much more exciting and learning a more real experience. More interest in asking similar questions-- getting to participate in real research has inspired some inking of permission to explore my own curiosities as they arise, rather than simply accepting current practice as an absolute best practice. Phones-- Using phones as equipment is effective in making the work feel more within my own reach.
Explanation of the theoretical computations and how they relate to the test procedure and seeing similar results between theoretical and experimental results.
The procedure to determine the amount of damage was very helpful in learning the effects.
Seeing and applying the formulas.
No lab
Text Response
Preparing the Excel sheet prior to lab was helpful in outlining the procedure for the lab and showed the steps to obtain the results.
Ability to compare results both theoretically and experimentally
The most effective part of this lab was the actual data being collected right in front of you. This lab allowed for you to visually see the displacements and then view the data the seismometer collected, if I was present during the lab.

Please list and explain the things you found LEAST EFFECTIVE about the learning experience

Experiment
Text Response
I found not having the proper material the least effective portion of the lab. The structural member being tested already had damage. It is not that big of a deal, but it takes away from the lab, for labs are supposed to be controlled experiments.
I know that this was just a quick introduction into natural frequency, but I feel like I didn't completely understand the whole background behind damping and the properties that influence natural frequency.
Going through all the equations in the beginning, although good as an introduction, was a bit confusing and I didn't really understand what was happening until we actually did the analysis. I was really confused when we were trying to figure out what weight to put on the end of the beam.
Just a time restraint on the lab.

No experiment
Text Response
Excessive manipulation of data in Excel can be a bore, but this lab was not to bad.
NA
I didn't collect the data... so the bit about that earlier isn't applicable. At times I was confused and lost... but it was possible to get reoriented and caught up. The explanation to somethings was confusing as I did not know what was what. Pictures and definitions would help.
Connection to general bridge design-- felt like an aside and didn't connect back to actual thesis if BRIDGE DESIGN. Three generated points of information leaves a lot of room for inconclusive reports, which is exciting, but not very academically rewarding in an immediate sense (especially when there's so much to learn, as it is). Derailment from scientific method-- we didn't get to come up with our own hypothesis to test and compare with the results. We didn't get to ask our own questions-- Definitely felt like a sidecar experience, detracting from a genuine sense of ownership or consequence. Hand-held through the technical section-- didn't get as much technical knowledge out of it because I felt that I was speculating rather than practicing, for better or worse.
Not performing the test procedure with iphone and beam.
The large amount of data for such a small experiment was the only hindrance.
Not seeing the actual set-up since I was in the 449 lab.

No lab
Text Response
It was challenging to understand the relationship between the natural period, circular frequency, cyclic frequency, number of cycles, amplitude, and damping ratio.
Getting background information since I was gone
The least effective part of this for myself, was having to read about the procedure and piece together what took place in the lab to gather the data that was given to me.

Please list and explain the things you found MOST EFFECTIVE about the instructor.

Experiment
Text Response
The instructor conveys the information articulately and concise. This makes for an easier understanding of the material being taught.
His enthusiasm for the material, and the background he gave about how he was trying to do research on the subject.
Answers to questions and explanations of the process were good.
The in-depth explanation of the laboratory exercise.
The explanation of the whole lab generally, then going back and going through step by step & answering questions along the way.
No experiment
Text Response
Clearly explaining the question, the method, and defining the objective.
NA
The technical knowledge, energy, and friendly mannor brought to the lab makes the otherwise opprobrious experience assistive.
His excitement-- the enthusiasm for discovering something new was infectious. Applying real data-- the two-part lab was actually really effective in feeling part of a real research project, saving us time in collection and focusing more on conclusions. It makes me wonder if it's better that the graduate students gathered and undergraduates discussed conclusions and evaluation. I think the other way around might be more appropriate, but we're all capable here at Oregon Tech.
Dr. Riley was very effective and detailed in explaining the processes and reasoning.
Willingness to help.
No lab
Text Response
The written procedure handout was very helpful in understanding the concepts, procedures, and expected results of the lab.
His eagerness and excitement towards the material
The most effective part about the instructor is that he is very energetic and engaged with his teaching. Although it was difficult to visualize how the lab procedure was carried out, due to lab absence, he supplied us with a great amount of information that allowed myself to catch up to the class.

Please list and explain the things you found LEAST EFFECTIVE about the instructor.

CE549, Monday afternoon
Text Response
His high ambitions sometimes puts a lot on our plates for lab, and we do not finish all the tasks required. But, I like that he has so much faith in us to accomplish everything he puts in front of us.
N/A
When we were running through the spreadsheet calculations, you were moving a little fast. I was able to keep up, but there were a few people that were falling behind.
It would be ideal to have the computer up near the screen and chalkboard to make points easier.

CE449, Thursday afternoon
Text Response
NA
Operates at a different level of understanding compared to some of the class...
Again-- didn't seem to tie very well to bridge design as much as rating or evaluation: just felt like an exploration of bridge mechanics, rather than a design situation, but maybe I'm getting ahead of myself
Some things said might be a little too fast for us to fully understand at the speed that you introduce the idea.

None, I was travelling to TRB.
Text Response
Some background information and practical field uses would be nice to learn about. This may have been discussed in class though.
Lots to do in the amount of time
I found that it was least effective for the instructor to have students pick their own points for viewing the dampening, as it was confusing for students to have different results and still be correct, but it is understandable as dampening varies with time.

Please list and explain any concrete suggestions for improving your learning in this laboratory.

Experiment
Text Response
I would suggest using the ram on the testing machine to put an initial displacement on the wood member. This then allows for a more controlled experiment. We then can put the same load each time we make a new cut to simulate damage.
Maybe making enough time during the lab to gather some more data or splitting into groups to test different scenarios. Like one group damages the beam close the support, one group does it in the middle, and another toward the cantilever end.
Making the lab a 2 or 3 part lab. Analyzing other structural members/structures.
No experiment
Text Response
I learn better when a lot is written on the board.
Pictures and definitions to specific vocabulary.
More emphasis on context-- there was a discussion of current bridge evaluation practices, but I feel it might be more effective to learn more about current bridge evaluation techniques first. Let us write our own hypothesis before we see the data (maybe read a prompt and come in with a hypothesis), to have some measuring stick. Required reading is tricky at Oregon Tech, though. You seem to have a lot listed, which is overwhelming and arguably dismissable. Then let us ask our own questions to explore, perhaps as a follow-up lab or term project.
Try slowing down on the excel spreadsheets. Sometimes it can be a little difficult to determine what to type in when you're a step ahead when we're still trying to discern what formula goes where and why that formula is being used.
I think it would have been more effective if the 449 lab period would have also got to see the experiment. I'm a visual learner so seeing it would have benefited me.
No lab
Text Response
This lab was presented very clearly, but I think it would have been more beneficial to attend the laboratory.
smaller class sizes are more effective
For travelers maybe a recording of the lab could have improved the understanding of the lab procedure.