Integrating a Smartphone-Based Vibration Experiment into an Engineering Course

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Abstract - **A smartphone coupled with a low-cost physical system can be used to conduct a meaningful at-home engineering experiment that provides an environment for experiential and personalized learning. The objective of this study is to improve students' understanding of the response of a dynamic system through integrating an at-home experiment into a lecture-only class using a smartphone as the measurement system. The paper reports on the use of the linear acceleration sensor in smartphones to conduct an at-home experiment to measure the vibration characteristics of a cantilever beam in a junior-level, systems dynamic course. All students in the class were provided with a spring steel beam and a C-shaped clamp. The students mounted their own phone at the end of the beam, and an app was used to record the acceleration of the beam for three different beam lengths. From the experimental data, the students were asked to determine the damped natural frequency of the beam and compare it to theory. The study was performed over three years with a total of 302 students. Data analysis of the short pre and post quiz conducted with the experiment showed that the at-home experiment had a positive effect on students' understanding of key concepts. Furthermore, written and verbal comments from the students showed that the students valued the learning they got from performing this experiment.**

Index Terms – Educational Technology, Experiential learning, Mechanical engineering, Mobile applications, Smartphone accelerometer, at-home experiments.

INTRODUCTION

Experiential learning improves students' understanding of key concepts. Students often perceive system dynamics and control concepts as mathematically abstract and have difficulty understanding these concepts [1]-[3]. A report by the National Research Council [4] has stated that "In all disciplines, students have incorrect ideas, beliefs, and explanations about fundamental concepts". An experiential learning approach, such as that offered by performing experimentation, offers additional experiences where students apply course concepts to engineering devices and systems to reconcile their misconceptions related to physical systems.

In many universities however, the laboratories are not given in the same semester or at the same time as the topics that are covered in the theory course, which makes it harder for students to relate the concepts covered in the course to the experiments performed in the lab. The widespread use of smartphones by college students and the availability of sophisticated sensors on these phones, such as those to measure acceleration and rotational velocity, make it possible to use these smartphones as portable at-home measurement systems. These types of experiments can enhance the learning experience of students without incurring much additional investment in resources and laboratory space. These experiences will improve the experiential learning of students in many courses including those that do not have a built-in laboratory component. Furthermore, providing personalized learning is one of the 14 Grand Challenges for Engineering in the 21st century as determined by a committee of the National Academy of Engineering [5]. At-home experimentation allows every student to use personal technology, such as a smartphone, to work at a pace tailored to the student's individual learning needs. In addition, at-home experimentation provides a useful tool that could augment the relatively new pedagogical approach of an inverted or flipped classroom experience [6], [7].

There has been considerable interest in performing measurements and experimentation in engineering programs outside of the traditional university laboratory. A sampling of the work in this area includes: simple home experiments to illustrate solid mechanics principals using household supplies and materials [8]; take-home experiments in fluid mechanics to illustrate basic concepts such as hydrostatics and the Bernoulli equation [9]; use of commercially available attaché cases or electronic trainers for conducting experiments at home in lower-division electronic laboratory courses [10]; digital design experiments using kits with programmable logic board [11]; Labs-to-go experiments that target dynamics of structures [12]; as well as experiments that target systems dynamics and control [13], [14].

Reference [15] reported on the use of smartphones in higher education showing that they are mostly used to look up for online resources. Reference [16] discusses the development of a system to access microlecture videos and other resources using smartphones. Reference [17] reported on students' perceptions of learning with mobile computing devices and the roles social media played. It found that mobile technology and social media provided opportunities for students to interact and to collaborate as well as to engage in content creation.

Reference [18] reviews a number of applications using sensors available on smartphones. These applications include health monitoring, physical activity detection, road and traffic information monitoring, and intelligent buildings monitoring. Previous work on the use of smartphone accelerometers in education includes the use of accelerometers in a simple pendulum experiment [19] where the smartphone is used as the pendulum bob. Another work [20] reported on the use of the mobile phone as an accelerometer for physics teaching where the smartphone was mounted on a cart sliding on a track. The air supply to the track was varied to control the amount of friction present in the system. In reference [21], the authors reported on using the accelerometer sensor in experiments involving an object sliding down an inclined plane.

The measurement accuracy of the smart phone accelerometer is proven to be sufficient in several studies including free fall of a smartphone [22], shaking rig experiment [23], and measuring structural vibration for structural health monitoring in civil engineering applications [24].

For at-home experiments that require system response measurements, such as those performed in [14], a custom circuit board was developed to interface the external sensors to the personal computer that controlled the experiment. Built-in sensors in smartphones eliminate the need for these boards since the sensor readings are directly sampled by the smartphone app, which reduces the cost of developing these at-home experiments.

The objective of this work is to improve students' understanding of the response of a dynamic system through integrating an at-home experiment into a lecture-only class using a smartphone as the measurement system. Understanding the dynamic response of physical systems is an important aspect of system dynamics. This subject forms the foundation for control systems education, which is one of the topics covered in mechanical and electrical engineering curricula.

While a smartphone has built-in sensors and data acquisition capability, it is not sufficient in most cases to use a smartphone alone to conduct meaningful engineering experiments that can be used to relate theory to the response of physical systems. It is also necessary to develop inexpensive hardware that can be used with the smartphone, especially when the experiment is performed at home with large enrollment classes. This paper illustrates this case by developing a low-cost simple beam and clamp system that is given to every student in the class to be used in conjunction with the student's smartphone

The remainder of this paper is organized as follows. The next section discusses the details of the smartphone-based vibration experiment. The following section discusses experiment implementation and results. The concluding remarks are given in the last section.

EXPERIMENT DETAILS

In this at-home experiment, students were asked to use their smartphone to measure the acceleration profile of a cantilever beam subjected to free vibration. All students in the class were provided with a 228.8 mm x 31.8 mm x 0.635 mm (9" x 1.25" x 0.025") spring steel beam with a double-sided tape attached at its end and a C-shaped clamp. Students were asked to clamp the beam at three different lengths they selected (and to use their own ruler to measure the cantilevered length of the beam). They were then asked to attach their smartphone to the end of the beam (the half-width line of the phone should be aligned with the end of the beam) and use a smartphone app to measure the vibration of the beam when the end of the beam is slightly displaced and released. Students were also asked to place a quarter-coin under the clamp to provide a more uniform holding force to the beam. Figure I show a typical setup. Students were also recommended to place a soft item, such as a pillow, under the phone to protect the phone in case it fell off the beam.

In this study, students were asked to download the application *Sensor Kinetics Pro* (which costs $2.99 for Android phones and $0.99 for IOS phones) on their smartphones. This application makes use of the linear acceleration sensor on the smartphone to capture the vibration of the beam in the z-direction. Before capturing the data, the students we asked to set the data capture rate to the maximum value allowed by the application (about 100 Hz for IOS and Android).

Figure II shows a screenshot of the application. This application was chosen because it allows the measured data to be saved into a comma-separated file which can opened by any data processing software, such as EXCEL to plot and analyze the data. The non-pro version of this App is available for free but it does not allow the measured data to be saved.

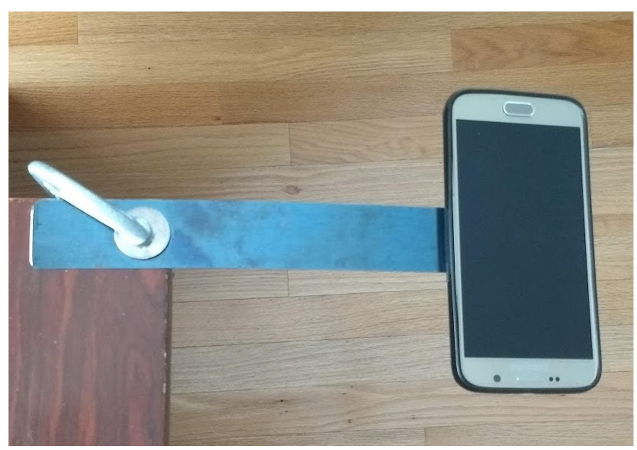

FIGURE I
A PHOTO OF THE CANTILEVER-BEAM EXPERIMENTAL SETUP.

After capturing the data with their smartphones, students were asked to transfer the data files to their personal computers. From the experimental data, the students were asked to determine the damped natural frequency of the beam at each of the three beam lengths and compare it to theory. For the theoretical comparison, students needed to determine the stiffness of the beam (modeled as a cantilevered beam with point load at its end) as well as obtain values for the effective mass of the beam (computed from beam dimensions and material properties) and the mass of the smartphone (obtained from manufacturer specifications or measured with a scale). From cantilever beam theory, assuming that the lowest vibration mode shape is the same as the static deflection curve, the effective mass of a cantilever beam is 23% of the beam mass [25]. The phone is modeled as a mass concentrated at the tip of the beam. Thus the equivalent system mass m_e is given by:

$$m_e = 0.23 \times m_b + m_p \qquad (1)$$

Where m_b is the mass of the cantilevered length of the beam and m_p is the mass of the phone.

The experimental setup and the details of the experiment were designed to provide an in-depth, hands-on, experiential illustration of several topics that are covered in the lecture-only course in which the experiment was given. All the topics related to the experiment (spring-mass lumped parameter modeling, effective mass, natural and damped frequencies) were covered in the course before the experiment was assigned. The experiment was also designed to identify misconceptions that student might have about these topics.

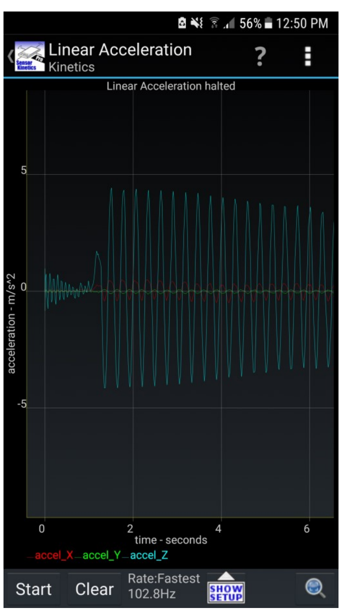

FIGURE II
SCREEN SHOT OF THE SENSOR KINETIC PRO APPLICATION

After completing the experiment, students were asked to submit a short report that includes the three measured response plots, the measured damped frequencies, the computed natural frequencies, as well as the correlation between measured and computed values. Students were also asked to provide any comments that they may have had on this experiment.

EXPERIMENT IMPLEMENTATION AND RESULTS

The experiment was implemented three times in the junior-level Systems Dynamics course (MCE 366) at the University of Rhode Island. This is a required, lecture-only course for mechanical engineering students. All the students enrolled in the course (a total of 302 students in the three years) performed the experiment.

Figure III below shows a typical set of data measured by one student. The student used a phone which has a mass of 157 grams to conduct the experiment. As seen by the data, the cantilevered beam system represents an underdamped free vibration system. The figure shows how the oscillation frequency decreases as the beam length increases (note that the horizontal scale is not the same for the three plots). For determining the damped oscillation frequency, most students choose to count the number of cycles per given time interval. Some students also used the signal amplitude information and the formula for the logarithmic decrement to determine the damping ratio in the system.

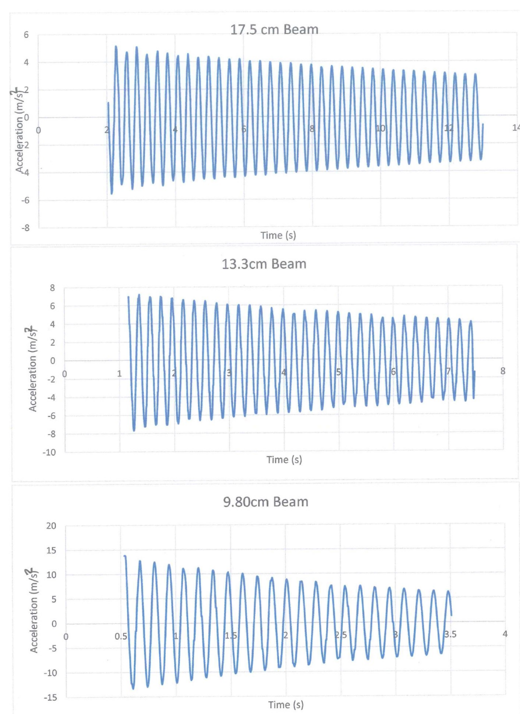

FIGURE III
OSCILLATION PLOTS MEASURED BY ONE STUDENT

To assess the effectiveness of this experiment on students' understanding of key concepts, students were given a five-question pre and post-quiz in class. Table I lists the quiz questions with the correct answers shown in bold face. The key concepts are listed in the last column in the table.

The first question measures students' understanding of using the simple mass-spring lumped parameter model as a representation for the dynamics of the cantilevered beam experiment. The second question relates to how one can determine (or not determine) the oscillation frequency of the beam. The third question checks students' understanding of the distinction between the natural frequency (which is theoretical and cannot be measured) and the measured oscillation frequency (or the damped natural frequency) that is obtained from the experimental data. The last two questions relate to how the natural frequency (or damped natural frequency) changes with a change in the beam length or the mass attached at the end of the beam.

TABLE I
PRE/POST QUIZ QUESTIONS AND KEY CONCEPTS

Question Number	Question Statement	Key Concept
1	A cantilever beam can be treated as a spring-mass system for vibration modeling (**True** or False)	Lumped-parameter modeling
2	If one has a plot of the oscillation amplitude vs. time of the beam, the oscillation frequency is determined by taking the inverse of the number of oscillation cycles in a given time interval (True or **False**)	Determination of oscillation frequency
3	The oscillation frequency that is determined from a plot of oscillation vs. time is the natural frequency of the beam (True or **False**)	Natural vs. damped natural frequency
4	The natural frequency of the beam increases with an increase in the beam length (True or **False**)	Natural frequency dependence on beam length
5	The natural frequency of the beam increases with a decrease in the mass attached at the end of the beam (**True** or False)	Natural frequency dependence on beam mass

The results from the pre/post quiz are shown in Table II. The table shows the percentage of correct answers for each of the five questions. The post percentages are higher than the pre percentages for questions 1, 4, and 5 in all years. For questions 2 and 3, the results are not consistent for all years. Question 1 has the highest percentage of correct answers (both for pre and post) of all the five questions since it asks students about a simple concept that every mechanical engineering student at this point in their education should have mastered. The second question has the lowest percentage of post correct answers, which could be due to the complicated wording of the question. The results for third question indicate that students still have a misunderstanding about the concept of natural and damped frequencies even after doing the at-home experiment as the results for the post are barley higher in the first year, lower in the second year, and higher in the third year. Note that in the assignment's write-up sheet, which was given to guide the students in performing this exercise, the term "damped natural frequency" was not mentioned explicitly and was referred to just as the measured oscillation frequency.

TABLE II
PRE/POST QUIZ RESULTS

Question Number	Percentage of Correct Answers					
	Spring 2016		Spring 2017		Spring 2018	
	Pre	Post	Pre	Post	Pre	Post
1	95	100	95	99	91	100
2	45	36	37	38	38	46
3	51	52	61	53	38	49
4	77	88	33	88	58	87
5	73	77	54	76	61	69
Average for Five Questions	68.2	70.6	56.0	70.8	57.2	70.2
Sample Size	89	83	82	76	99	108
Class Enrollment	97		89		116	

Questions 4 and 5 show a higher post answers than the pre answers, especially for the second and third years data. This indicates that through the analysis needed to compare the measured data to theory, students figured out how natural (or damped natural) frequency depends on the length and effective mass of the beam. Overall, the average percentage of the post correct answers for the five questions is higher than the pre average for all the years, indicating that the at-home experiment had a positive effect on students' understanding of key concepts.

To provide further information on how students perceived this at-home experiment, below are some quotes from students who provided comments on this experiment:

> "… Overall, the project was fun to conduct and was effective in terms that it was a real application to what we were learning in class."
>
> "…The experiment proves the theory to be correct."
>
> "… Overall, this was a gratifying experiment displaying the effects of dampening present in every aspect of day-to- day life."
>
> " … This experiment made it possible to understand damping and the effects of it in real-life applications."
>
> "…Overall, the independent study was a fun and engaging way to experiment with natural frequency and observe how the length of a beam affects the frequency of a mass-spring system."

"…Overall, the experiment demonstrated these results and supports the initial hypothesis that the damping frequency is lower than the natural frequency."

"... This lab helped the students learn how to work independently."

From the students' written and verbal comments, the author got the impression that the students valued several things in this at-home experiment: the opportunity to work with a real system, the opportunity to relate measured data to theory, the chance to perform an experiment independently, and to document and understand the effect of damping in real systems. Few students in each year wrote negative comments about the experiment. All these comments came exclusively from students whose experimental results did not match the theoretical prediction due to errors such as wrong use of units, wrong formulas, or wrong mass values.

After the experiment reports were graded and returned to the students, the pre and post quiz results were shared with the students to explain the key concepts that the experiment was trying to convey. Also a discussion of some of the main errors that were observed in the reports was shared with the class so students can avoid repeating these errors in the future. These errors included wrong use of units (for example, mixing Hz with rad/s), incorrect mass data for the phone they used, incorrect computation of the effective mass, and incorrect mounting of the phone on the beam (for example, the phone is not centered with the beam). The last error could affect the shape of the oscillation response curve.

CONCLUSIONS

Integrating an experiment into a course using a smartphone acceleration sensor proved to provide an engaging assignment for students that helped them solidify concepts covered in the junior-level system dynamics course using their own personal technology. The low cost of the beam and the clamp set (total cost less than $5 per set) and their usage in more than one course offering make this experiment affordable even in large classes.

The main purpose of this at-home experiment was to give students the chance to perform experimental measurement of the oscillation frequency of a cantilevered beam and to relate the measured data to concepts covered in the course such as natural and damped frequencies, effective mass, and damping. Data analysis of the short pre and post quiz conducted with the experiment showed that the at-home experiment had a positive effect on students' understanding of key concepts. Furthermore, written and verbal comments from the students showed that they valued what they learned from this experiment.

In relating the experimental results to theoretical values, students have to be concerned with practical issues such as how the beam is supported, the accuracy of their measurements and analysis techniques, the proper units to use, and errors that could have affected their results. These considerations provide rich experiential learning skills that computer simulations of the same problem do not provide. The paper showed that a smartphone coupled with a low-cost physical system can be used to conduct a meaningful at-home engineering experiment that provides an environment for experiential and personalized learning.

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