## Smartphone-Based Labs for Engineering Vibration Class

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**Abstract:** Lab-centered instruction is a critical component of engineering pedagogy. The creation of effective lab-centered assignments is more difficult than creating theory-only assignments due to additional requirements including space, equipment, software, and maintenance. Smartphones, and their embedded sensors, provide an alternative method for students to collect instructive data without the extensive requirements of traditional in-person laboratory spaces. Smartphone applications such as "Phyphox" enable the user to interact with smartphone sensors to view and download data. This approach is especially beneficial for adding lab assignments to classes without dedicated lab space, such as upper-division technical electives. This paper presents two lab assignments that were created for a senior-level vibration course that requires students to collect accelerometer and microphone data. Pros and cons of the assignments are discussed as well as student perceptions of the assignments.

## INTRODUCTION

Both theoretical and hands-on lab instruction are critical elements in effective engineering education. Among the most important learning objectives of lab-based instruction is familiarizing engineering students with instrumentation, data collection and data processing techniques [1]. In many engineering programs this is achieved through periodic lab instruction that often takes place in dedicated lab spaces with appropriate equipment. Due to the high costs of measurement systems, these labs often consist of students working together in small groups, sometimes with multiple groups per day rotating through the lab space. While this approach is effective, it can lead to a less than ideal learning experience. Poor setups, faulty equipment, or even too much help from peers can limit the effectiveness of hands-on lab assignments [2]. Additionally, in-person labs can be difficult for non-traditional students and can present undesirable health risks if equipment is not properly sanitized after use. Finally, the traditional approach to engineering labs makes it very work intensive and expensive to add a lab assignment to a class that does not have a dedicated lab space.

It would be helpful for an instructor to create lab assignments that provide the benefits of realistic lab work without the need for dedicated lab spaces, expensive equipment, and the hassle or cost of maintaining sensitive equipment and software. One alternative to traditional hands-on labs is a simulated lab where the physics and instruments are represented within a software environment [3]. Popular lab software packages including PhET Simulations, Physics Lab, BEAKER, and Labster provide realistic virtual environments that allow students to perform experiments, collect data, and gain knowledge about physical phenomena without the costly overhead that comes with a traditional lab space [4]. There are many positive aspects of virtual labs and much has been published regarding the positive impact of virtual lab work [5][6][7]. Some instructors have taken one step further, creating lab assignments that provide all the benefits of traditional labs while using items and instruments that are readily available. This paper builds on prior research by sharing an engineering measurement lab that students can perform by accessing the instruments in their smartphones [8].

The smartphone is a modern miracle, with the average device containing significantly more computational power than the Apollo 11 guidance computers [9]. In additional to impressive computing power, the average smartphone also houses an array of instruments including accelerometers, gyroscopes, magnetometers, barometers, microphones, cameras, etc. With a high-speed computer and a suite of modern sensors, an average smartphone has all the trappings of an engineering lab, although tapping into those sensors is not obvious; that is where the app "Phyphox" comes in. Phyphox was developed at a university in Germany (RWTH Aachen) to enable educational physics experiments requiring only a smartphone. An example of the Phyphox interface is shown in Figure 1. The app enables the user to tap into any instrument on their smartphone to record and export measurement data [10][11]. The app has already been used by educators around the world to help students to gain a better understanding of fundamental concepts in physics classes [12][13][14][15].

The combination of the modern smartphone and apps like Phyphox provide opportunities for engineering instructors to design meaningful lab assignments that can be performed on campus or even at home without access to specific lab equipment or software. This enables hands-on and instructionally valuable experiential assignments to be added to a course while saving both time and money. This paper presents two lab assignments that were added to an engineering vibration course (ME 4150 at Weber State University). The addition of these assignments helped to bridge the gap between theoretical discussion and real-world observations.

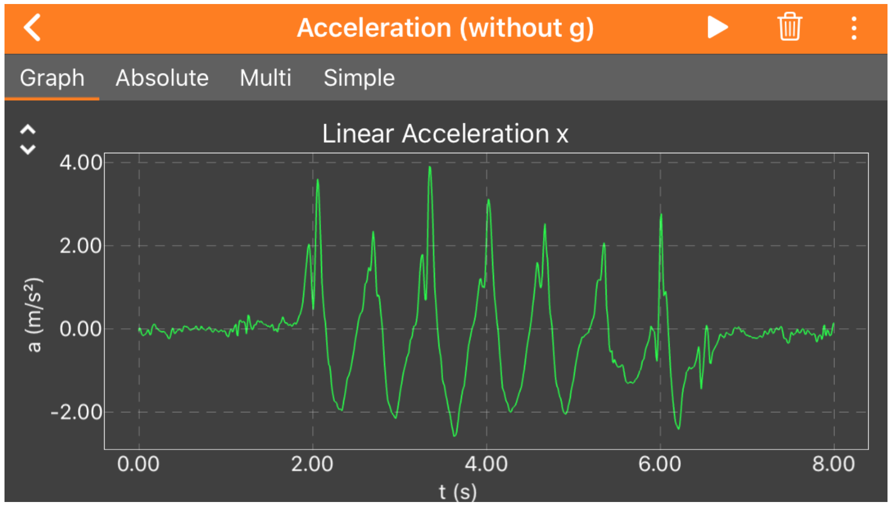


Figure 1: A smartphone screen capture while running the Phyphox app while collecting data using an onboard accelerometer. The green peaks correspond to steps taken while holding the smartphone.

## METHODS

While other educators have created physics labs using smartphone sensors [16][17][18][19]; these prior examples were designed to help students learn fundamental concepts in physics classes. Only one other study that we found used smartphone sensors to teach measurement techniques in an engineering context [8]. The purpose of this project was to create two new labs that students can perform at home using their smartphones, that mimic the traditional lab experience on campus as much as possible.

Before completing the assignment, students were given some in-class training on how to use their smartphone to collect lab data. This provided an opportunity for the instructor to avoid some common errors such as students downloading the wrong app, misunderstanding app operation, and relying on values from graphical displays on the app rather than downloading numerical data. In class, students were introduced to the accelerometer features and experimented with the app by collecting data while walking and jogging a few steps. This helped familiarize students with the accelerometer sensitivity as well as the orientation of the x, y, z coordinate system relative to their phone. Students also practiced pulling numerical data from the phone (in .csv or .xls format), transferring it to a computer, and generating plots. This introductory step helped students to avoid getting stuck on basic app operation while performing labs at home. Most students caught on quickly and (as they are engineering students) were excited by their newfound ability to extract data from their smartphone sensors.

Lab assignments were presented to students through learning management software (i.e., Canvas). The lab assignment instructions were intentionally brief and focused on describing what the students needed to accomplish, but not providing a complete step-by-step process. This allowed the students to consider the specific details for how the lab should be performed and make their own informed decisions for execution. Students were allowed to conduct the lab assignments in groups but each student was required to submit a unique lab report.

**Accelerometer Lab Methods**

The accelerometer lab requires students to use the accelerometer on their smartphone to measure the frequency of their washing machine motor during wash and spin cycles. One of the primary objectives of the lab is to introduce students to accelerometers and to familiarize them with realistic vibration data. A vibration class is often extremely mathematical and students grow accustomed to seeing the crisp and clean sinusoidal responses that are predicted by the governing equations. True vibration data are rarely so clean, typically containing several harmonic frequencies as well as noise. The students also learn that the vibration data they collect are highly dependent on the nature of the material interfacing between the smartphone and washing machine. Later in the class we discuss that there are many disconnects between the motor motion and measured vibration as the motor and washing machine frame need not vibrate at the same frequency, which is also true for the machine frame and the accelerometer mass. Students are then prompted to experiment further by placing more than one material between their smartphone and the washing machine to investigate the damping effects.

The students are then expected to extract, process, and interpret the data they collect. These raw data need to be analyzed and trimmed before applying a fast Fourier transform to determine the dominant frequencies of the signal. While the lab is relatively simple, students are introduced to a 3-axis accelerometer, the subtleties of setup, data analysis, and data plotting.

**Microphone Lab Methods**

The second lab pushes the students deeper into measurement topics and requires data collection and data post-processing that is less intuitive. Students are instructed to drop coins on a hard surface (specifically a nickel, dime and quarter) one at a time while recording the resulting sound. Students must consider their environment when collecting these data to ensure they have adequate measurement quality (e.g., avoiding background noise or working in a room with minimal echo). Students are asked to perform a fast Fourier transform on the resulting data files to identify the first fundamental frequency or lowest strong tone generated by the ringing coin. This frequency is primarily a function of the coin diameter and material parameters.

After calculating the first fundamental frequency of the three coins students are then asked to a) identify a mystery coin from a frequency spectrum and b) estimate the first fundamental frequency of a half dollar coin (detailed lab information is provided in Appendix B). The students must perform a basic scaling analysis to relate coin diameter to frequency in order to answer the second question. While the lab remains simplistic and is easily performed using only a phone and common items, the assignment provides students first-hand experience with valuable measurement fundamentals. Perhaps most importantly, this lab helps demonstrate to students the strong connection between vibration and acoustics and the viability of using acoustic data as a diagnostic tool for vibration problems.

## RESULTS

Both lab assignments provided students with opportunities to gather realistic vibration data that differed significantly from the plots that students were accustomed to seeing in the book. Many students initially thought they must have collected erroneous data, but typically after closer analysis, students realized that real data is, in fact, messy. Both labs also provided information that enabled students to experience some of the topics that are usually only discussed from a theoretical perspective in a vibration class. This section will review some of the major findings from each lab assignment as well as student response to the assignment.

**Accelerometer Lab Results**

The first lab requires the students to use the accelerometer on their smartphone to measure the frequency of their washing machine motor during wash and spin cycles. The average student was extremely confused when they first plotted the data from this experiment. Students commonly plot the data with individual symbols rather than connected points, which are incredibly difficult to see as oscillatory motion. Students also commonly looked at the entire data set (sometimes over ten seconds long) which made it hard for them to see small oscillations. The first step is for them to learn to interpret the data set, clip meaningful sections and view the data in the same plot. Figure 2 shows an example of the type of vibration data that students were able to collect using a smartphone and the Phyphox app. This data has been appropriately clipped and labeled. The particular plot shows clear oscillatory motion with the spin cycle, but this is less clear during the wash cycle. Both material interfaces demonstrate the same frequency (as would be expected) but the towel provides additional damping. The data is choppy which opens up a valuable discussion on the Nyquist frequency.

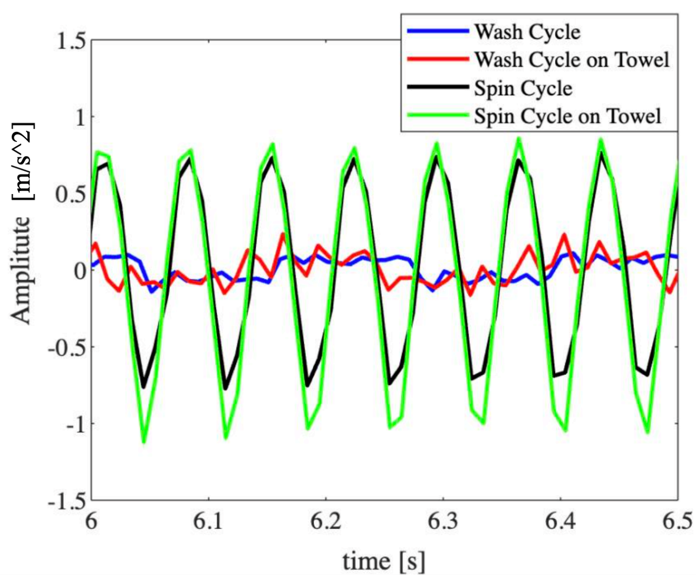


Figure 2: Data plot of accelerometer data recorded using a smartphone and Phyphox.

Figure 3 is a fast Fourier transform of the data shown in Figure 2. The data collected on the spin cycle show a peak frequency at approximately 14 Hz and the wash cycle data show a peak frequency at approximately 4 Hz.

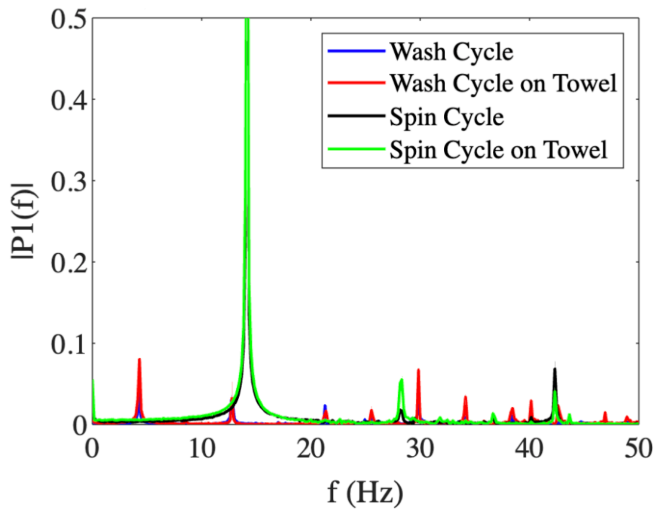


Figure 3: Frequency plot (FFT) of washing machine vibration data.

**Microphone Lab Results**

For the microphone lab students dropped U.S. coins (dime, nickel and quarter) on a hard flat surface and recorded the acoustic response with the intent of measuring their natural frequency. The coin's natural frequency is largely governed by material density, elastic modulus and diameter ( $f \sim (1/D)\sqrt{E/\rho}$ ). All three coins are made from similar copper-nickel composition (dime & quarter 91.6% Cu, nickel 75% Cu) and thus have similar densities and elastic moduli; the coin diameter is mostly responsible for differences in tone between the coins. Students had to go through the process of collecting clean acoustic data, calculating the fast Fourier transform and picking the first fundamental peak frequency for each coin. These values were plotted as a function of coin diameter and used to predict the dominant acoustic frequency for an untested coin (U.S. half dollar). An example result is shown in Figure 4.

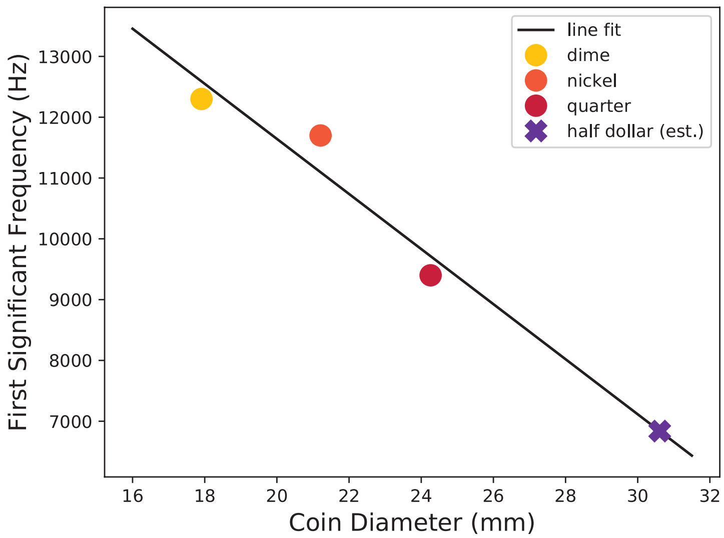


Figure 4: Plot of fundamental frequency vs. coin diameter from microphone lab.

**Student Response to Lab Assignments**

Lab assignments were generally well received and feedback was predominantly positive. My impression was that students found the lab assignments to be more difficult than the average lab, but were typically not opposed to the work as they felt that the practiced skills would be applicable to their future careers.

After the completion of the class students were given a short anonymous survey to assess their opinions of the lab assignments. The questions and student responses are summarized in Table. Students generally agreed that these assignments a) helped them to gain a stronger understanding of engineering vibration, b) provided a more realistic engineering experience than the average assignment in their program of study, and c) caused them to think and reflect more about the topic. Responses were a little lower on questions 4 and 5 referring to the Microphone Lab. I suspect this is because acoustics wasn't expressly covered in the course textbook and this may have felt outside of the mainstream discussion. It may also have been that coins may have felt less appropriate for an engineering assignment to the students. Having them record the response of a motor or something mechanical may improve the response on this lab.

Table 1: Summary of student response to smartphone-based lab assignments.

| **Question**<br>*(Scale: 1-Strongly Disagree, 2-Disagree, 3-Somewhat Disagree, 4-Neither Agree nor Disagree, 5-Somewhat Agree, 6-Agree, 7-Strongly Agree)* | **Mean Response**<br>n = 10<br>*(st. dev.)* |
|---|---|
| 1. The Accelerometer Lab Assignment helped me to gain a stronger understanding of engineering vibrations. | 6.4<br>*(1.0)* |
| 2. The Accelerometer Lab Assignment provided a more realistic engineering experience than the average assignment in my program of study. | 6.6<br>*(0.7)* |
| 3. The Acceleration Lab Assignment caused me to think and reflect more about the topic than the average assignment in my program of study. | 6.2<br>*(1.2)* |
| 4. The Microphone Lab Assignment helped me to gain a stronger understanding of engineering vibrations. | 5.7<br>*(1.3)* |
| 5. The Microphone Lab Assignment provided a more realistic engineering experience than the average assignment in my program of study. | 5.9<br>*(1.5)* |
| 6. The Microphone Lab Assignment caused me to think and reflect more about the topic than the average assignment in my program of study. | 6.1<br>*(1.2)* |

## Conclusions

This effort has shown that modern technology provides significant potential for providing students with valuable educational experiences that were previously only possible within a traditional on-campus lab. The diversity of instruments and sensors in a modern smartphone provide a unique opportunity for helping students gain hands-on experience collecting and analyzing data, and the effort described in this report has only scratched the surface. The sensors mentioned in this article could be used for other topics in engineering. Beyond these two sensors, there are additional sensors common to smartphones, including gyroscopes, magnetometer and barometers, could be used to create many other useful lab exercises. Additionally, inexpensive cameras have recently become a powerful measurement tool for computer vision technologies such as lane assist and face recognition. An entire class could likely be dedicated to studying the use of cameras as a measurement tool as well as the many image processing and computer vision algorithms in use today. My future efforts on this topic will involve creating smartphone-based experiential lab assignments for teaching students about the many ways that cameras can be used to make unique measurements.

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## APPENDIX A – LAB ASSIGNMENTS

### Accelerometer Lab Assignment

***Objective:***

The purpose of this lab is to help students become familiar with:

- Phyphox, a smartphone app for collecting measurements
- Collecting vibration data using an accelerometer
- Creating a spectral plot using a Fast Fourier Transform (FFT)

***Instructions:***

Start by downloading the app "Phyphox" onto your smartphone and familiarize yourself with the software. Phyphox enables the user to pull data from the many sensors embedded in a smartphone. Choose "Acceleration (without g)" from the list and press the play button (triangle). This starts the data collection process. Note the recording can be paused and then deleted or exported. Click on the button with three vertical dots. This provides an option to export the raw data in a variety of formats. I recommend exporting data as an Excel file.

You will use the app to collect accelerometer (vibration) data while your washing machine is running on a 1) wash cycle and 2) spin cycle. I recommend the following steps for collecting each measurement:

1. Start recording acceleration data on the app
2. Hold still for a small period
3. Place your phone on the top of the washing machine

   (take care so that it won't be knocked off)

4. Allow data collection for at least 5 seconds
5. Take phone off the machine
6. Hold still for a small period
7. Stop the recording
8. Export the data set

Repeat these two measurements (wash & sping) using two different materials between your phone and the machine (4 total data sets) – Options include the case (assuming it is not completely smooth and provides some friction, plastic (Saran) wrap, wax paper, two-sided tap, a thin foam packaging sheet, etc.

Once the data has been transferred to your computer, I recommend using Python or Matlab to clip the data (reduce to only the portion that applied to the measurement), plot and analyze the collected data. The phone will collect data for 3 axes, and the total magnitude. Choose to use data from a single axis or total magnitude and justify your choice. Use a Fast Fourier Transform (FFT) to create a spectral plot for each test case. Identify the first fundamental frequency for each washing machine cycle and comment on how/if changing the material between the washing machine and phone altered the results.

<u>Write a short lab report that shows the collected data and answers the questions below. Please don't produce eight individual data plots. Data should be combined on related plots as much as possible.</u>

Questions:

1. How did the material between the washing machine and phone affect the data?
2. What are the first fundamental frequencies you measured for each cycle?
3. Which data did you end up using (single axis or total magnitude) and why did you decide to use this data?
4. Your spectral plot has a max frequency value. What determines this max value?
5. After performing this lab, what do you think you could do to improve data accuracy?

**Microphone Lab Assignment**

***Objective:***

The purpose of this lab is to help students become familiar with:

- Collecting acoustic data (free of excessive measurement noise)
- Spectral analysis (frequency analysis) using Fourier Transform
- Generating and interpreting spectral plots
- Scaling as a means of simple modeling

***Instructions:***

To perform this lab you will need three coins (nickel, dime & quarter) a hard surface and a quiet room. You will be using the "Audio Scope" function of the Phyphox app to collect the sound generated by a coin falling onto a hard surface. Before collecting data make sure you have maximized the collection duration of "Audio Scope" to 500 milliseconds. I also recommend dropping the coin nearly on its face so it rattles a bit before coming to rest on the hard surface.

Repeat the process for the nickel, dime and quarter. I recommend exporting the data as a .xls file, though any format is fine. (Recording quality may be improved by collecting data under a heavy blanket).

Compute the Fourier transform for each of the collected data files (I recommend using Welch's Method, signal.welch() in Python, pwelch() in Matlab). Plot the resulting frequency data and identify the lowest resonant frequency (first large peak) for each coin. If we perform a dimensional analysis of a vibrating coin (assuming coins have the same aspect ratio, diameter to thickness ratio) we can derive the relationship below:

$$f = const. \cdot \frac{1}{D}\sqrt{\frac{E}{\rho}}$$

where $\boldsymbol{f}$ is the vibration frequency, $\boldsymbol{D}$ is the coin diameter, $\boldsymbol{E}$ is Young's modulus and $\boldsymbol{\rho}$ is density. A nickel, dime and quarter all have similar composition, each being at least 75% copper with the remaining fraction nickel, thus each coin will have a similar value for $\boldsymbol{E}$ and $\boldsymbol{\rho}$; we would expect the excited frequency to primarily vary inversely with coin diameter $\boldsymbol{D}$. Plot the lowest resonant frequencies identified as a function of coin diameter ($\boldsymbol{D}$ values: nickel = 21.21 mm, dime = 17.91 mm, quarter = 24.26 mm). Fit a line to the data and use this linear model to predict the lowest resonant frequency for a half dollar coin ($\boldsymbol{D}$ = 30.61 mm).

<u>Write a short lab report that shows the collected data and answers the questions below. Include the specs for the microphone on your phone, especially sample rate (these are listed for most smartphones on the Phyphox website). Include a plot of the spectral estimate for each coin, as</u>

well as a plot showing resonant frequency as a function of coin diameter with your predicted value for a half dollar coin.

Questions:

1. Do you think you could use the collected data to predict the lowest resonant frequency for a penny? Why or why not?
2. Estimate the potential error of using your line fit to predict resonant frequency given a specific coin diameter? In what range would you expect the lowest resonant frequency of a half dollar exists?
3. What are the highest frequencies for your spectral estimation returned values? What do you think governs this cutoff?
4. Suppose you decide to test your estimated resonant frequency for a half dollar, but are only able to find a half dollar minted before 1964 and thus 90% silver. Would you expect this coin to have a resonant frequency higher or lower than the value predicted? Why?
5. What coin do you think produced the spectra below?