2023 Annual Conference & Exposition
Baltimore Convention Center, MD | June 25 - 28, 2023
The Harbor of Engineering
Education for 130 Years
ASEE
Paper ID #36812

# Mobile Phone-Based Contact and Non-Contact Vibration Sensing for Structural Dynamics Teaching Laboratories

**Dr. Charles Riley, Oregon Institute of Technology**

Dr. Riley has been teaching mechanics concepts for over 20 years and has been honored with both the ASCE ExCEEd New Faculty Excellence in Civil Engineering Education Award (2012) and the Beer and Johnston Outstanding New Mechanics Educator Award (2013). While he teaches freshman to graduate-level courses across the civil engineering curriculum, his focus is on engineering mechanics. He implements classroom demonstrations at every opportunity as part of a complete instructional strategy that seeks to overcome issues of student conceptual understanding.

# Mobile Phone-Based Contact and Non-Contact Vibration Sensing for Structural Dynamics Teaching Laboratories

## Abstract

Acceleration-based dynamic sensing has been available for many years and numerous researchers have made effective use of the accelerometer available in mobile phones for measuring vibrations at frequencies up to half the sampling rate of the phone. Manufacturers of mobile phones, tablets, and other devices are adding new sensors with each new model creating the potential to expand the engineering laboratory from the confines of university laboratories and into the wider world. Students can collect dynamic measurements with their own mobile phones in addition to, or rather than, expensive laboratory equipment.

In this paper, six methods of vibration sensing are compared to results from a high-precision accelerometer, demonstrating the benefits and drawbacks of various contact and non-contact sensors available on mobile devices, but specifically on the iPhone 12 Pro and later models. Sensors include the accelerometer, magnetometer, RGB camera, and most notably the LiDAR sensor. Non-contact sensing, which is valuable for measuring model structures that might be significantly impacted by the added-mass effect of an attached mobile device, is demonstrated with LiDAR sensing, video-based object tracking, video post-processing, magnetometer, and an app-based implementation of the stroboscopic effect. Contact sensing, which is generally more sensitive, is demonstrated using the on-board accelerometer and compared to a high-precision seismic accelerometer, as well as the non-contact methods. Various mobile apps are cataloged and described for data collection, analysis, and post-processing. These tools represent a variety of phone-based methods for the vibrations or structural dynamics laboratory, allowing students to explore and compare various methods of sensing. The range of applicability of each sensing method is summarized to inform instructors considering phone-based laboratory activities. Instructors can select a method suited to their experiment and learning objectives.

## Introduction

Structural dynamics and mechanical vibrations courses may have various prerequisite courses depending on the instructor, department, or academic program and may or may not be preceded by courses introducing mathematics, physics, kinetics and kinematics, solid mechanics, structural analysis, Fourier analysis, sequences and series, fundamentals of vibrations, and others. The most unlikely prior knowledge for civil engineering students is signal processing and sensor technology, while mechanical engineers may not have experience with large structures. Thus, the benefits of the laboratory as a place to explore structural vibrations may be reduced because a student lacks fundamental knowledge in a particular area. However, these topics can be learned through effective implementation of laboratory exercises with physical models instrumented to measure time-dependent forcing and response [1]. Laboratories are a particularly effective environment for students to learn structural dynamics concepts and methods of analysis [2]. Rich laboratory experiences are increasingly possible thanks to low-cost computing and control platforms like Raspberry-Pi and Arduino [3] but are even more accessible with phone-based sensors and tailored apps [4,5].

Most structural dynamics textbooks [6,7] follow a straightforward progression of topics, focusing on single-degree-of-freedom (SDOF) systems first, then exploring various forcings, well-described continuous systems, and finally multi-degree-of-freedom (MDOF) systems and modal decomposition approaches. Frequency-domain methods may be emphasized or de-emphasized, depending on the textbook and course, but they provide a very effective inductive means of exploring structural response. In civil engineering, the primary goal is to describe MDOF systems subjected to random vibration as a basis for time-history analysis of buildings in earthquakes. As inductive approaches to teaching and learning suggest [8], the end goal of a course should be described to students first, then the foundational and intermediate concepts of the class can be treated in context. With contextualized foundational understanding of vibrations principles, students can approach increasingly complex vibrating systems with enthusiasm and focus both on the results of real measurements as well as their limitations [9]. Mobile-phone-based investigations can provide this experiential foundation and inspire further inquiry by students. Numerous authors have documented positive student response to phone-based experimentation [1,10,11].

Robust experimentation for vibrating structures and models has long been restricted to laboratories in possession of expensive sensors and data acquisition systems, but these capabilities are increasingly available on mobile devices with a growing number of onboard sensors, accessible data streams from these sensors, and apps that provide data acquisition and post-processing tools, file storage, and sharing. As these tools have matured, the ability to conduct and document scientific experiments using ubiquitous mobile devices has advanced to the point that dedicated laboratory equipment is rendered obsolete and students carry all the tools they need in their pockets [4].

The term “sensing” can describe a complex pathway from physical phenomenon, through hardware, software, and user interface, historically requiring a power supply, sensors, signal conditioning, data acquisition, and computer post-processing. With all these tools available in modern mobile phones, measuring a quantity using a mobile phone requires little more than a purpose-built app and a few gestures. But understanding the "sensor" and its processing requires a deeper understanding. This paper will attempt to describe and demonstrate the value of phone-based "sensors" for measuring structural vibrations, with sensors classified as either contact or non-contact. The nature of these sensors, including hardware, software, and file formats will be provided.

It should be noted that more expensive equipment that can be replaced (or used for comparison) includes precision accelerometers, laser doppler, laser interferometers, and high-speed video recording and analysis equipment. Sacrifices in precision are reasonable in an instructional setting, given the benefits of access to phone-based tools, real-time data analysis, and live plotting of frequency spectra. As this paper will demonstrate, these sacrifices need not be significant and the tools now available are very robust.

This paper will focus on the measurement of free vibration response, primarily for small laboratory-scale models, using phone-based apps and sensors. Details of forcing will not be discussed. Controlled forcing with a shake table will not be necessary, although a complete course all but requires this important tool to provide a basis for a student to predict structural response to a random excitation or ground motion. In fact, the benefits of some of these sensors to collect non-contact response of laboratory structures beyond simple free vibration is where their true value exists and will be the subject of future research.

## Methods

The experiments and apps described in this paper are focused on the iPhone and iOS operating system. The iPad Pro, iPod Touch and other devices may also offer similar capability, depending on the generation of the device. Some Android-based phones are capable of higher sampling frequencies, improving their range of applicability, but they were not tested for the purposes of this paper. LiDAR has been available on certain Apple products starting with the iPhone 12 Pro.

The iPhone LiDAR sensor uses direct time-of-flight (dToF) sensing, one of many approaches that measure the time taken to send and receive light pulses as a way of sensing depth in the 3D environment. The specific technology varies based on the type of device, but Apple products employ a technology to emit photons using a vertical cavity surface emitting laser (VCSEL) that takes advantage of silicon chip-making technology to miniaturize the laser array. In working mode, 576 points fill the field of view of the iPhone camera at roughly $60^\circ$ by $48^\circ$ [12], and light pulses, reflected off objects in the environment, are received by a single-photon avalanche diode (SPAD) that functions as the camera or receiver. The depth map that is ultimately available to app developers is processed within the phone's architecture based on a combination of inputs from the LiDAR sensor as well as the phone's camera, accelerometer, gyro, and magnetometer. The LiDAR sensor improves the accuracy of depth sensing while the camera allows for greater density. The technology represents a significant leap in mobile sensing and more details are available for the interested reader [12]. Put as simply as possible, 576 LiDAR points are combined with RGB camera values to produce a depth map with a maximum resolution of the camera, which is 1080p, at 60 frames per second. The 1080p resolution has 1920 pixels horizontally and 1080 pixels vertically, for a total of 2,073,600 pixels, although the number of cloud points in a single-frame is usually less than this. Some apps are available to capture time varying point clouds, but the PhyPhox app, employed in this study, calculates a single depth value based on a user-selected patch in the field of view, with a processing step to capture either the *closest* values, an *average* of all values in the patch, or a *weighted* average. In most of the experiments here, the *closest* values are used to improve the sensing for only the primary structure of interest, which is in the foreground. In summary, a LiDAR-based distance measurement is the culmination of many steps involving the LiDAR sensor itself, the camera and other sensors on the phone, Apple software, user decisions regarding placement of the phone and target, the size of patch selected, and the selection and processing of points within that patch. The user is left with something that functions relatively simply, providing the position of a vibrating object as a function of time at a sample rate of 60 Hz (based on the camera frame rate).

### *Equipment*

All measurements in the experiments described here employed an Apple iPhone 13 Pro running iOS 16.3. Apps employed are all available on the Apple App Store. The Vibration Analysis and Video Tachometer apps are free with reasonably priced in-app upgrades that support file sharing, external devices, and higher precision measurement. The PhyPhox app is available free for both iOS and Android. The accelerometer on board the iPhone 13 Pro is a micro-electromechanical systems (MEMS) accelerometer [4].

The reference acceleration-sensing system consists of a PCB digital ICP mobile signal conditioner (485B39) and high-precision 10-V/g accelerometer (626A04) that were connected via the iPhone lightning port (as a microphone) with data acquired and visualized using the Vibration Analysis app. The PCB 626A04 accelerometer chosen for these experiments has the greatest sensitivity available in PCB's catalog, with a particularly low frequency range (0.1-200 Hz) and acceleration limit (±0.5g peak).

### *Phone-based apps*

While many apps are devoted to data acquisition of single sensors, there are at least two apps available that are dedicated to accessing the suite of sensors available on mobile phones: PhyPhox [13], produced by physicists at RWTH Aachen, and Physics Toolbox [14], by Vieyra Software. PhyPhox is used exclusively in this paper because of its better resolution (60 fps versus 30 fps) and the ability to create or modify your own experiment using XML coding. PhyPhox's in-app data analysis including plotting, zoom, data point identification, and differences, as well as its file export and clean intuitive interface, are more effective than Physics Toolbox. PhyPhox also has robust international language support.

Third-party apps employed in the experiments described here include Vibration Analysis [15], Video Tachometer [16], and Video Physics by Vernier [17].

Vibration Analysis has impressive real-time frequency spectrum plotting. It can access and plot all three axes of the iPhone accelerometer and includes many windowing functions to improve either frequency estimates or amplitude measurements. It can also export data for post-processing and save data collection directly on the phone. It samples at 100 Hz, making measurements of frequencies up to 50 Hz possible. An in-app purchase will allow for measurement through the lightning port on the phone, which is how the high-precision PCB system was employed in this study.

Video Tachometer allows adjustment of the frame rate of the video displayed on the screen by increments of 0.01 Hz within a range from 0.5 Hz to 240 Hz. By sampling at the same frequency as that of a vibrating system, a vibrating object will appear fixed in place on screen.

Video Physics allows recording or selection of a video. Within the video a distinctive pixel, such as the edge of a vibrating object or ball bounced across the frame, can be selected for tracking. Once selected, the app identifies the location of this feature as it moves. A scale can be identified to relate pixels to distance so that vibrations are accurate in both displacement and time. It has a maximum sample rate of the standard video frame rate: 60 Hz.

### *Post-Processing Methods*

Post-processing of measured signals generally takes two approaches in the experiments described here: either time history data is analyzed directly to identify a natural period or a Fast Fourier Transform (FFT) is performed within an app or as a later step in a software package like Excel or Matlab to identify dominant frequencies in a signal. In both cases, steps can be taken to improve the accuracy of results.

In many of the experiments that follow, values in a time series are measured within the PhyPhox app. More accurate results can be obtained by doing two things:

1. Count as many periods as possible where the signal appears well behaved. Pick points at the peak of a first cycle and at the peak of a much later cycle. Divide the duration by the number of cycles to calculate the period in seconds. Invert the period to obtain the frequency in Hz.
2. Identify cycles that have a data point representing a clear peak. Avoid selecting points for analysis that are offset from what appears to be the obvious peak.

The sample rate of the data collection is the primary determinant of the precision of the frequency measurement. For example, if the sample rate is 60 Hz, the sampling duration is 1/60 or 0.01667 seconds. If a harmonic signal with a frequency of 2.40 Hz is being measured, the period is the inverse, 0.41667 seconds. The maximum error of this measurement is 0.01667/0.41667 or 0.0400 or ±4%. Taking the steps outlined above and measuring the period of 10 cycles improves this accuracy by the same factor, so ±0.4%. In this way, the error of any given measurement of period can be quantified and the steps above can be taken to reduce it.

The FFT is available in both the PhyPhox and Vibration Analysis apps to produce a frequency spectrum for a measured signal. The precision of a dominant frequency identified as a peak in a frequency spectrum is a function of the duration of the data collection, sampling frequency, and the window type used to address so-called signal leakage. A larger discussion of these issues is beyond the scope of this paper and is addressed in many references devoted to signal analysis and the particulars of FFT analysis [18]. Taking the same example above, 10 cycles of a

0.41667-second signal measured at 60 Hz would result in 10 x 0.41667 x 60 or 250 samples. But the FFT can only be applied to a number of samples that is a factor of 2. With 256 being the closest value, let us assume we have collected 256 samples. The frequency resolution of a FFT is equal to the sampling frequency divided by the number of samples, so 60/256 or 0.234 Hz. For the 2.40-Hz frequency we are attempting to measure, the frequency resolution is 0.234/2.40 or 0.0975 or 10%. This is much worse than the 0.4% accuracy using the time series method. It can be improved by either collecting more data or by applying a Gaussian window and frequency interpolation, which is implemented in the Vibration Analysis app. If 512 samples are collected, an 8.53-second duration at 60 Hz, the frequency resolution improves to 0.117 Hz or 5%. For every doubling of sample duration, the frequency resolution is cut in half. Thus, to reach the same or better accuracy obtainable using time history analysis, the duration of the sampling would need to be increased to 8,192 samples for a duration of 136.5 seconds or 2.27 minutes for a frequency resolution of 0.007 Hz or 0.3% of the 2.40-Hz signal. In many cases, the vibration of the structure of interest damps out at such long durations.

In the following sections, experiments will be described, their results presented, and a brief discussion offered. A broader discussion of the methods and their applicability will be offered last.

## Experiments

Four experiments are reported here to demonstrate the capabilities of a variety of phone-based sensors, with a particular focus on the iPhone-based LiDAR depth sensing as measured using the PhyPhox app.

1. The first experiment compares the iPhone LiDAR to a high-precision accelerometer and phone-based MEMS accelerometer as measured by the Vibration Analysis app as all equipment is placed at the tip of the same freely oscillating cantilever.
2. The second experiment compares more phone-based non-contact methods of sensing on a smaller cantilever that is not capable of supporting a phone and for which the added mass effect would be considerable if an accelerometer were attached.
3. The third experiment compares the measurement of two modes of vibration for a two-story frame model measured using the on-board MEMS accelerometer and iPhone LiDAR. A fast Fourier transform (FFT) is applied to the resulting LiDAR displacement data to identify modal frequencies.
4. The fourth experiment examines the noise in the LiDAR signal in an attempt to characterize the precision and random error of the LiDAR sensor.

## *1. Contact and Non-Contact Methods (high-precision accelerometer, MEMS accelerometer, LiDAR, stroboscope)*

In this first experiment, a simple cantilever was set up that could support all equipment necessary and vibrate at a relatively low frequency. As shown in Figure 1, the phone was placed overhanging the cantilever so that the rear-facing camera and LiDAR sensor could reference stable ground below. The cantilever was excited while the LiDAR depth data was collected with PhyPhox based on the standard patch and the "average" aggregation method. The experiment was repeated with accelerations logged using Vibration Analysis and collected by the PCB system. The experiment was repeated again with accelerations logged using Vibration Analysis but collected from the on-board accelerometer.

Figure 1. Experimental setup #1 with iPhone 13 Pro and PCB accelerometer at the tip of a flexible cantilever.

Results of the accelerometer measurements are shown in Figure 2 with a clear peak visible in each frequency spectrum: 2.358 Hz for the PCB system and 2.360 Hz for the on-board accelerometer. The LiDAR measurement indicated that 11 cycles took 7.127 seconds, for a period of 0.423 seconds, or a frequency of 2.365 Hz. The Video Tachometer app was employed and registered a natural frequency of 2.40 Hz. These results are summarized in Table 1.

```
1)   2.358: 0.002970
2)  21.381: 9.127E-06
3)   7.070: 6.411E-06
4)   4.692: 6.138E-06
5)  14.139: 5.310E-06
6)   9.472: 1.510E-06
7)  61.239: 1.038E-06
8)  47.438: 8.976E-07
Interpolation of frequencies
```

```
Axis: Mic
Sample rate: 8000 Hz
FFT size: 32768 (4.10 sec.)
Window: Gaussian
```

```
1) 2.360: 0.02961
2)   0.00: 0.0006136
3)24.065: 0.0002865
4)21.245: 0.0002800
5)20.004: 0.0001995
6)23.162: 0.0001859
7)17.300: 0.0001318
8) 7.143: 0.00009259
Interpolation of frequencies
```

```
Axis: Z
Sample rate: 99.7 Hz
FFT size: 1024 (10.3 sec.)
Window: Gaussian
```

Figure 2. Vibration Analysis frequency spectra for the PCB system (left) and on-board accelerometer (right).

Each of these measurements is within the precision of the sensors considered. The agreement is excellent and demonstrates the effectiveness of both on-board accelerometers and LiDAR sensing.

Table 1. Summary of sensor, app, post-processing method, and result for four methods of vibration sensing.

| **Sensor** | **App** | **Postprocessing** | **Frequency (Hz)** |
|---|---|---|---|
| Precision PCB accelerometer, signal conditioner | Vibration Analysis | In-app frequency spectrum | 2.358 (ref) |
| iPhone MEMS accelerometer | Vibration Analysis | In-app frequency spectrum | 2.360 (0.1%) |
| iPhone rear-facing LiDAR | PhyPhox | In-app period measurement | 2.365 (0.3%) |
| RGB Camera (rear-facing) | Video Tachometer | In-app, frequency selected to stop apparent motion | 2.40 (1.8%) *** |

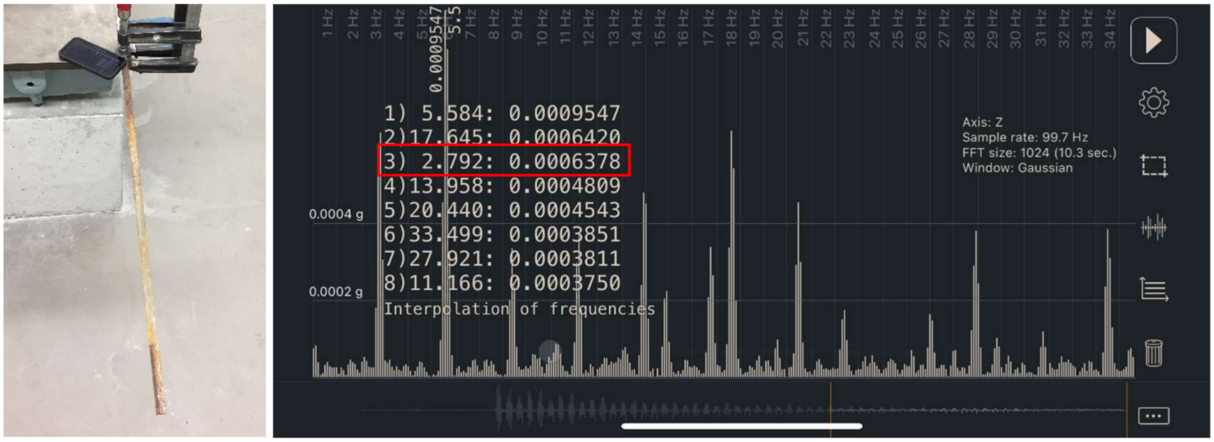
*** The Video Tachometer app was used to analyze this system, with a 2.40 Hz frequency identified (1.8% higher than reference accelerometer), but a lighter phone served as the tip mass on the cantilever; thus the higher frequency measured is reasonable and the 1.8% difference is not directly comparable to the other results. This app is explored further in the next experiment.

### 2. *Non-Contact Methods Comparison (stroboscope, magnetometer, LiDAR, video recording, edge detection)*

A very flexible steel cantilever incapable of supporting a phone or high-precision accelerometer was clamped to a rigid steel fixture as shown in Figures 3-9. The steel cantilever had a length of 0.75 m and a cross section of 16 mm by 2 mm. Analytically, the first natural frequency should occur at 2.97 Hz, but measurement results averaged 2.75 Hz perhaps attributable to a more flexible support, a heavier beam, and deviations in beam thickness.

One contact-based method was attempted, by placing a phone in contact with the cantilever near the support to minimize its influence on the system (Figure 3). Other non-contact methods employed the iPhone front-facing LiDAR (Figure 4), iPhone rear-facing LiDAR (Figure 5), magnetometer (Figure 6), video recording with stopwatch (Figure 7), Video Tachometer (Figure 8), and Video Physics app (Figure 9). The sensors, apps, post-processing methods, and results are summarized in Table 2.

### *Contact-Based Accelerometer Measurement with Vibration Analysis*

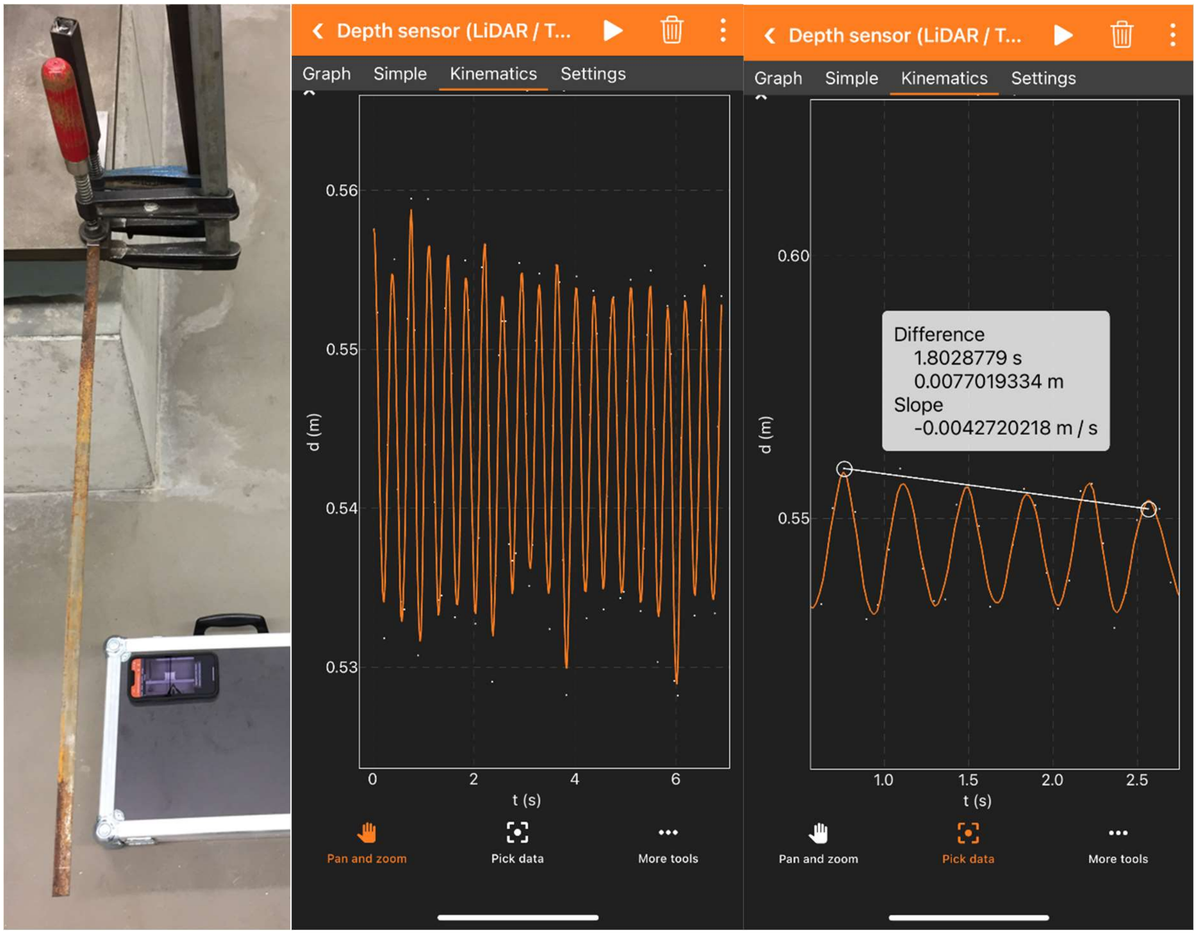


```
1) 5.584: 0.0009547
2)17.645: 0.0006420
3) 2.792: 0.0006378
4)13.958: 0.0004809
5)20.440: 0.0004543
6)33.499: 0.0003851
7)27.921: 0.0003811
8)11.166: 0.0003750
Interpolation of frequencies
```

Axis: Z
Sample rate: 99.7 Hz
FFT size: 1024 (10.3 sec.)
Window: Gaussian

Figure 3. iPhone placed in contact with beam near the support for contact-based measurement with on-board accelerometer. Vibration Analysis output with peak at 2.79 Hz.

### *Front-Facing LiDAR with PhyPhox*

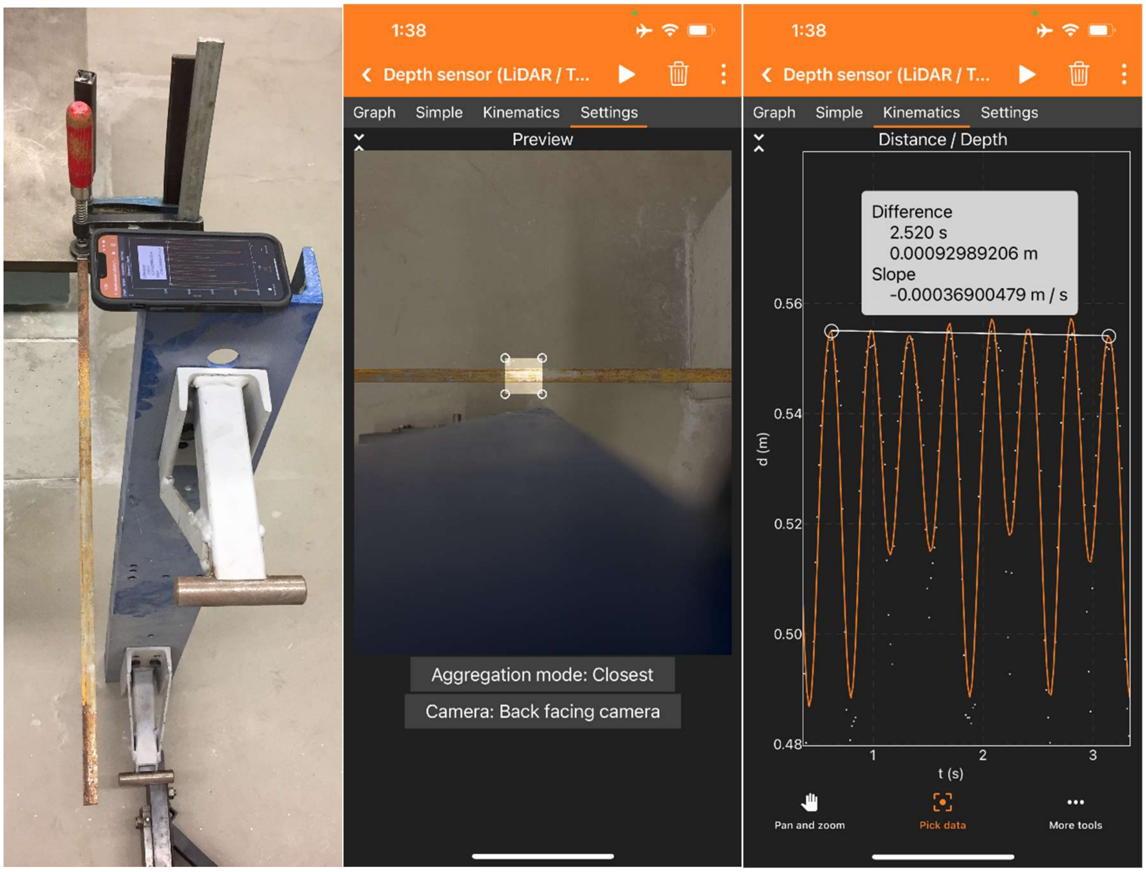


Difference
1.8028779 s
0.0077019334 m
Slope
-0.0042720218 m / s

Figure 4. Front-Facing LiDAR measurement with phone placed below the beam.

Five cycles take 1.8029 seconds for a period of 0.3606 seconds, a frequency of 2.77 Hz.

### *Rear-Facing LiDAR with PhyPhox*



Aggregation mode: Closest

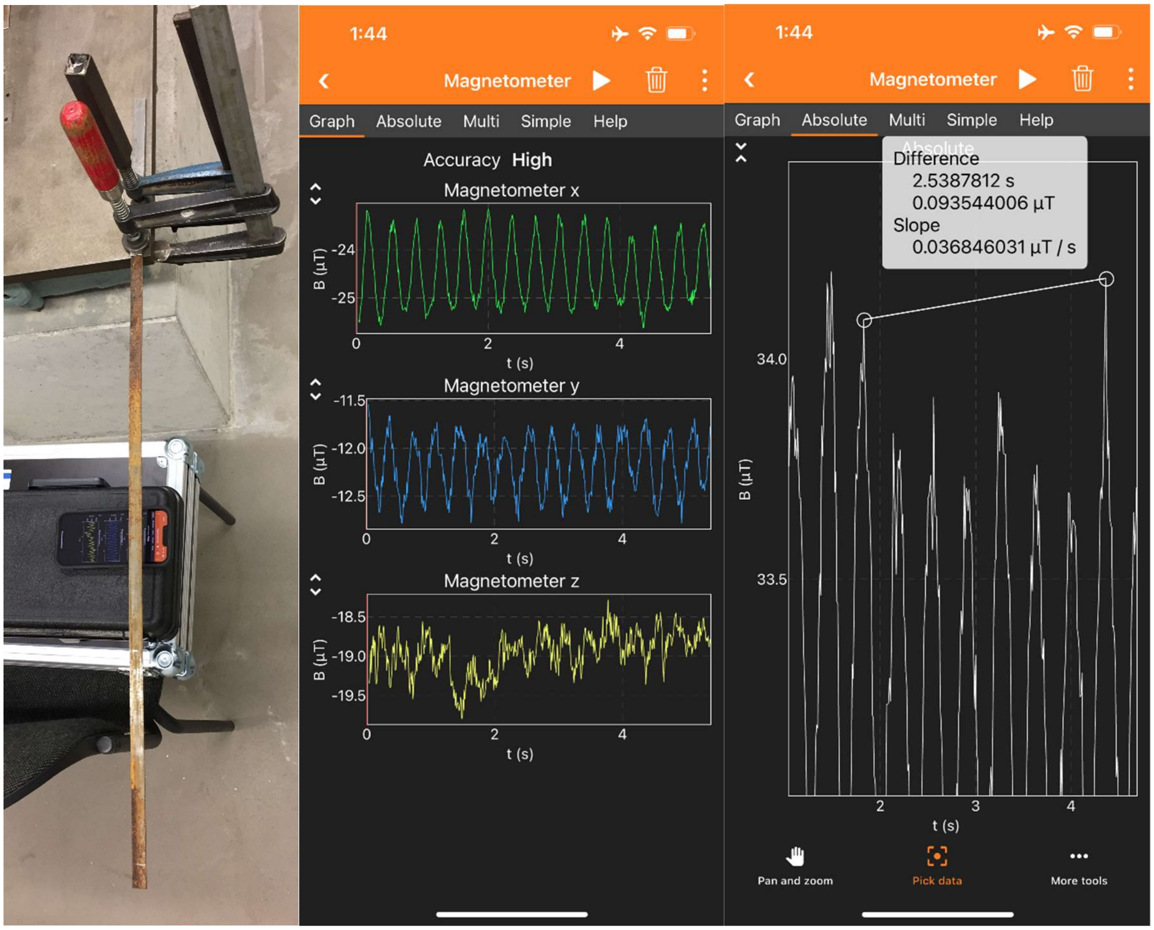
Camera: Back facing camera

Difference
2.520 s
0.00092989206 m
Slope
-0.00036900479 m / s

Figure 5. Vibrations measured with rear-facing LiDAR placed above the beam with small patch and “closest” aggregation mode.

Seven cycles take 2.520 seconds for a period of 0.360 seconds, a frequency of 2.78 Hz.

### *Magnetometer with PhyPhox*



Difference
2.5387812 s
0.093544006 µT
Slope
0.036846031 µT / s

Figure 6. Magnetometer measurement with phone placed in close proximity (~5 cm).

The phone was placed below the vibrating cantilever and magnetometer measurements were recorded. In post-processing, seven cycles take 2.5389 seconds for a period of 0.3627 seconds, a frequency of 2.76 Hz.

*Video-based measurement of natural period*

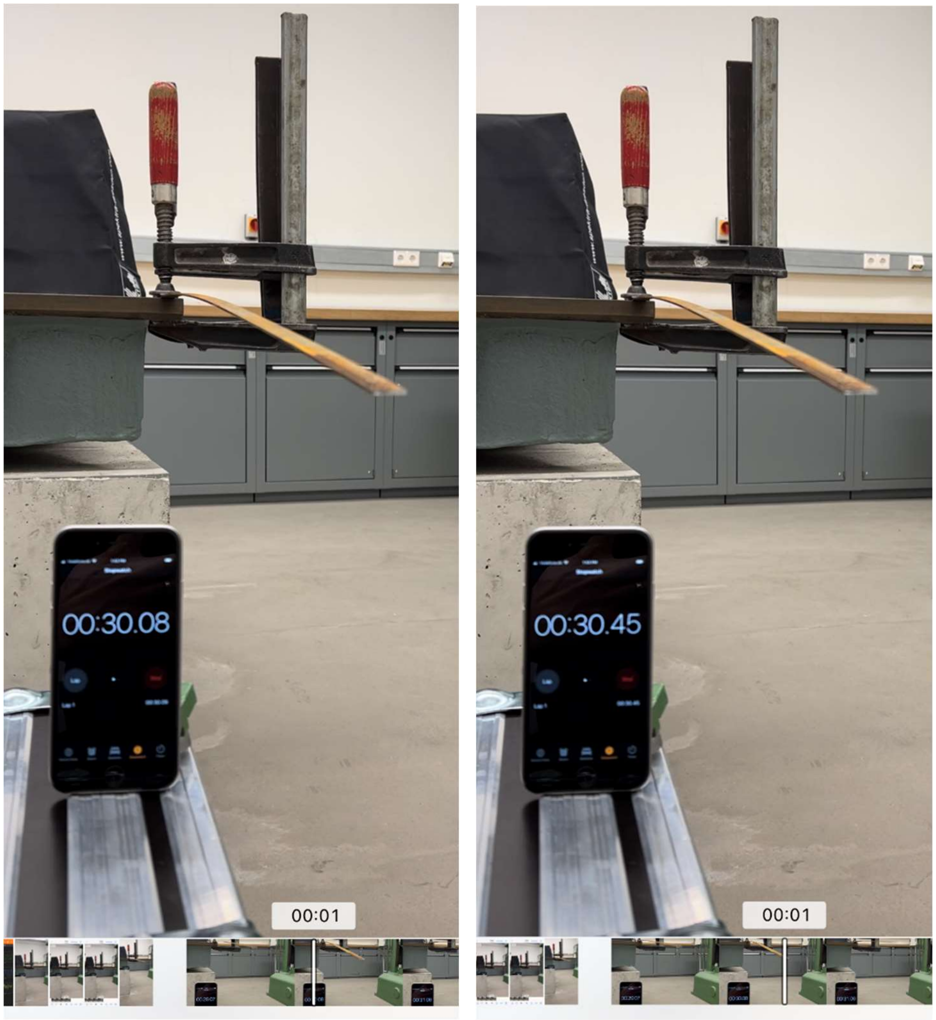


Figure 7. Frames of slow-motion video with cantilever at the bottom of the cycle.

Video frames were selected to identify a single cycle based on the cantilever at the lowest point. A period of 0.37 seconds was identified, or a frequency of 2.70 Hz. This method is highly subjective and is limited by both frame rate (60 or 240 fps) and the precision of the stopwatch (0.03 seconds), but it is conceptually valuable to measure the duration of a single cycle. Of all the methods considered, this one has the greatest potential for human error in the post-processing. At the same time, it provides the most physical visual depiction of a cycle. The precision can be improved by measuring the duration of multiple cycles as described earlier.

*Stroboscopic Effect with Video Tachometer*

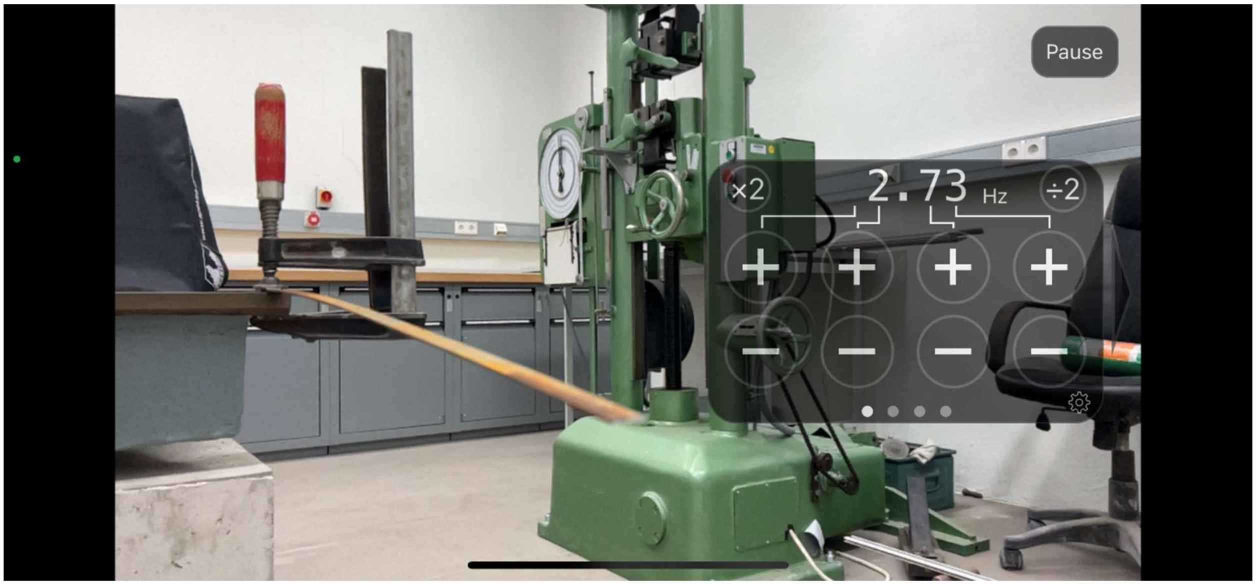


Figure 8. Screen capture of Video Tachometer app set to 2.73 Hz to stop the motion of the vibrating cantilever in the frame.

The Video Tachometer app was set to a frequency of 2.77 Hz based on previous measurement and adjusted until the cantilever appeared still in the frame, which occurred at 2.73 Hz.

### *Edge Tracking with Video Physics*

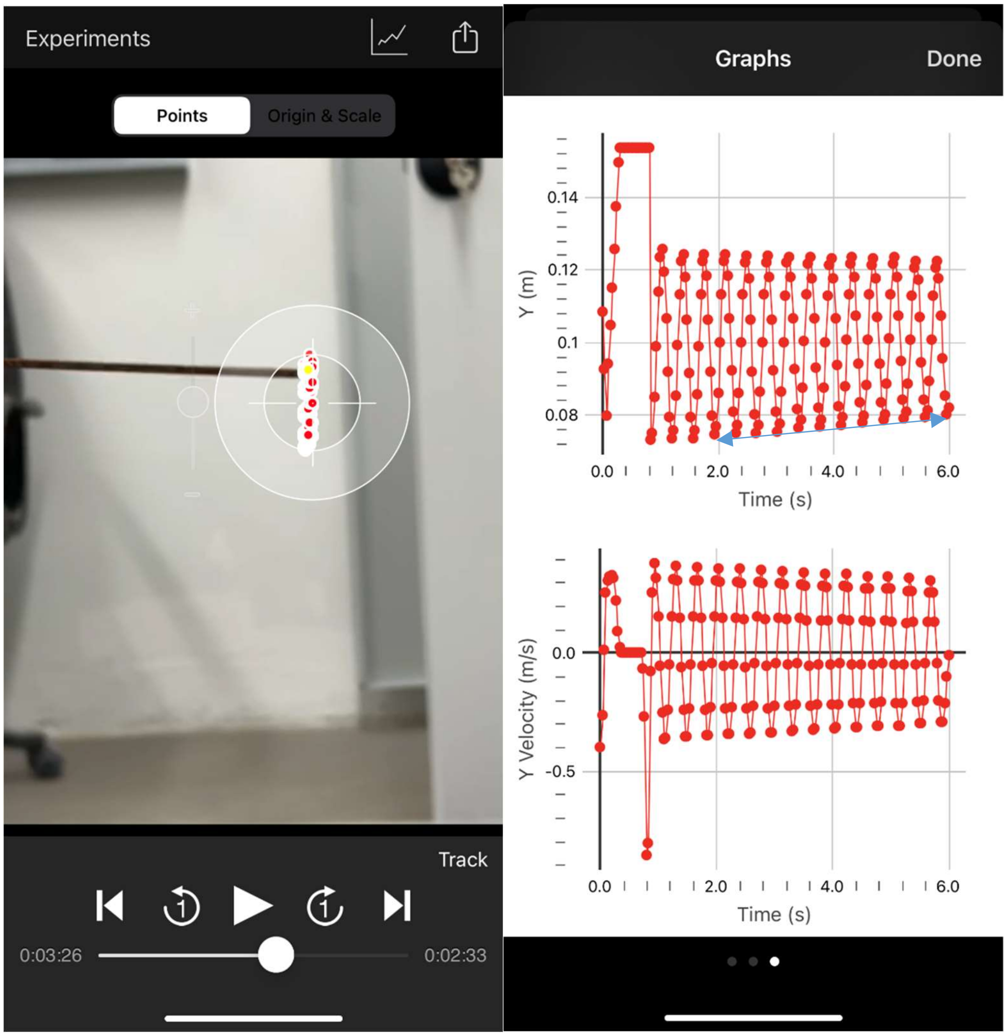


Figure 9. Video Physics measurement with cantilever tip selected for tracking and feature position plotted versus time.

The Video Physics app allows feature selection and tracking. With 11 cycles taking 4 seconds, a frequency of 2.75 Hz was identified.

Table 2. Summary of sensor, app, post-processing method, and natural frequency measured for by seven methods.

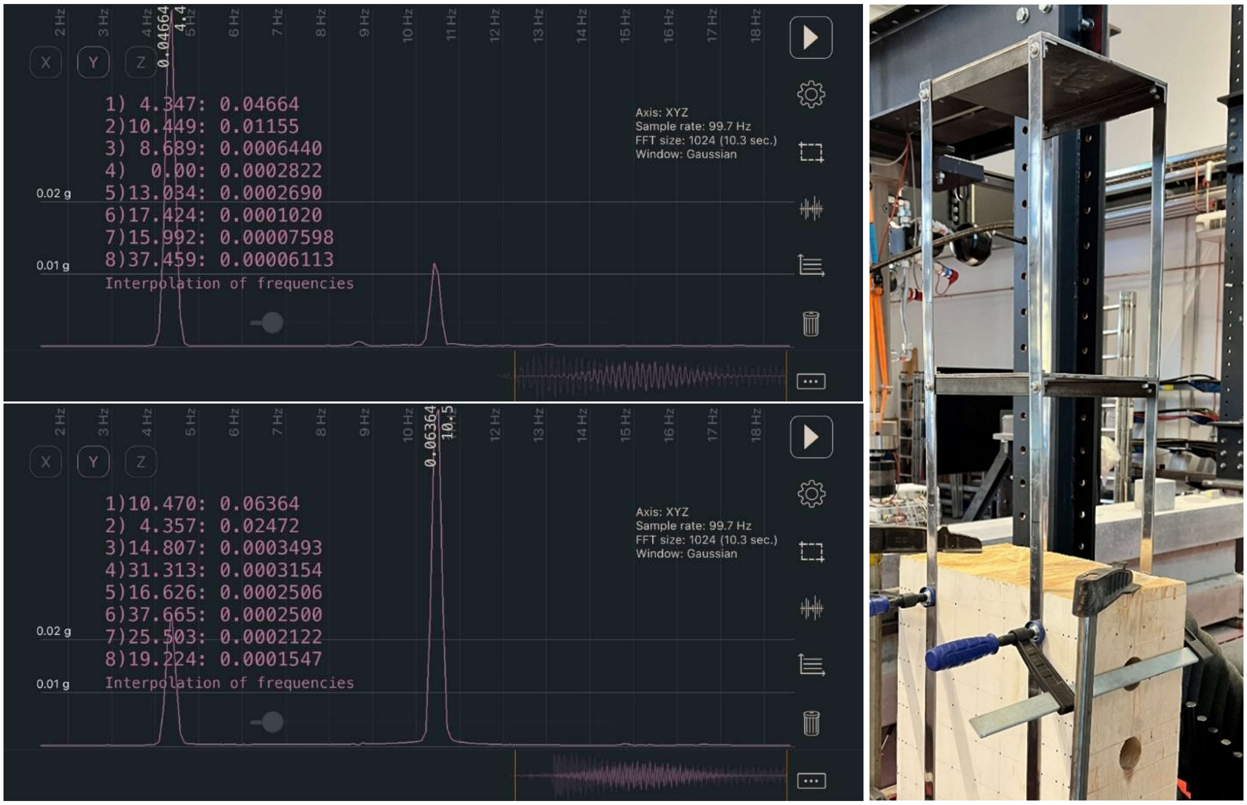
| **Sensor** | **App** | **Post-processing** | **Frequency (Hz)** |
|---|---|---|---|
| iPhone MEMS accelerometer | Vibration Analysis | In-app frequency spectrum | 2.79 |
| Front-facing iPhone LiDAR | PhyPhox | In-app frequency spectrum | 2.77 |
| Rear-facing iPhone LiDAR | PhyPhox | In-app frequency spectrum | 2.78 |
| Magnetometer | PhyPhox | In-app period measurement | 2.76 |
| RGB Camera with stopwatch in frame | iPhone Camera App | Peak-to-peak cycle measurement | 2.70 |
| RGB Camera | Video Tachometer | In app, frequency selected to stop apparent motion | 2.73 |
| RGB Camera | Video Physics | In-app period measurement based on edge tracking | 2.75 |

The values measured by each method range from 2.70 to 2.79 Hz, representing a maximum difference of roughly 3%. As with the first experiment, this is very good agreement and approaches the precision available by any individual sensor/method.

### *3. Two-story frame model*

A two-story frame model employing 16-mm by 2-mm columns, with steel angle and plate floor elements, was measured using both contact and non-contact methods. A phone was placed on the first-floor plate; the first two modes were excited and their frequencies were measured using the Vibration Analysis app (Figure 10). The phone was then removed from the floor plate and set up on a ladder next to the structure at the same elevation as the first floor (Figures 11 and 12). LiDAR measurements were taken with a patch encompassing the whole first floor edge visible in the frame and the "closest" setting chosen in PhyPhox. The time series data was collected in free vibration with both the first and second modes excited by imposed displacements consistent with the mode shape. Data were exported as comma-separated variable (.csv) files and a FFT was performed. The time series, patch selection, and resulting frequency spectra are shown in Figures 11 and 12. Results are compared in Table 3.

The results indicate excellent agreement for the first mode; the 4.34 and 4.35 Hz frequencies appear in all analyses because the second mode could not be independently excited. The second mode was more challenging to excite independently and a more significant difference (4.8%) between the contact (10.47 Hz) and non-contact (10.92 Hz) methods appeared. The higher frequency registered by the non-contact method could also be a result of the added mass of the phone used in the contact method. The greater influence of this added mass on the second mode compared to the first mode can be explained by the out-of-phase displacements of the first and second floors.



```
1) 4.347: 0.04664
2)10.449: 0.01155
3) 8.689: 0.0006440
4)  0.00: 0.0002822
5)13.034: 0.0002690
6)17.424: 0.0001020
7)15.992: 0.00007598
8)37.459: 0.00006113
Interpolation of frequencies
```

```
Axis: XYZ
Sample rate: 99.7 Hz
FFT size: 1024 (10.3 sec.)
Window: Gaussian
```

```
1)10.470: 0.06364
2) 4.357: 0.02472
3)14.807: 0.0003493
4)31.313: 0.0003154
5)16.626: 0.0002506
6)37.665: 0.0002500
7)25.503: 0.0002122
8)19.224: 0.0001547
Interpolation of frequencies
```

```
Axis: XYZ
Sample rate: 99.7 Hz
FFT size: 1024 (10.3 sec.)
Window: Gaussian
```

Figure 10. Vibration Analysis measurement with phone placed at first floor of a two-story frame model; first mode excited (top) and second mode excited (bottom).

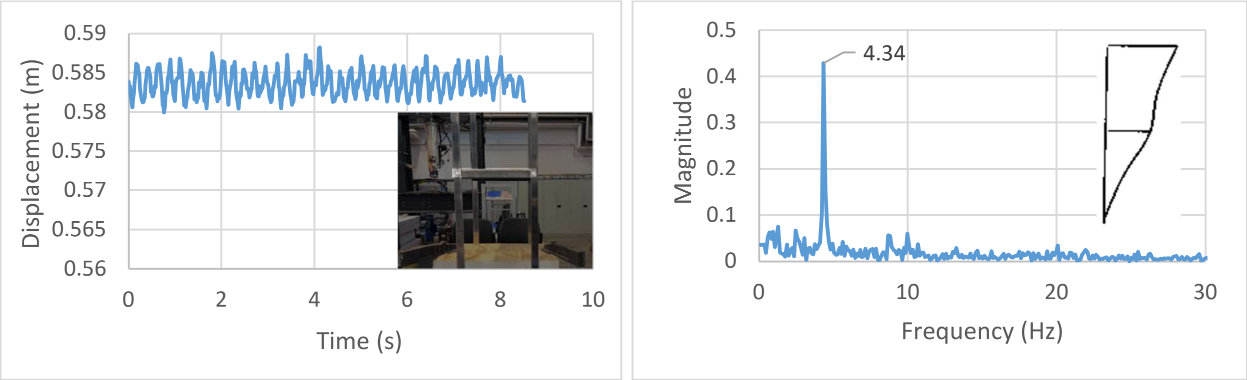


Figure 11. LiDAR Measurement at 1st floor level with 1st mode excited. Time series (left) and associated frequency spectrum (right).

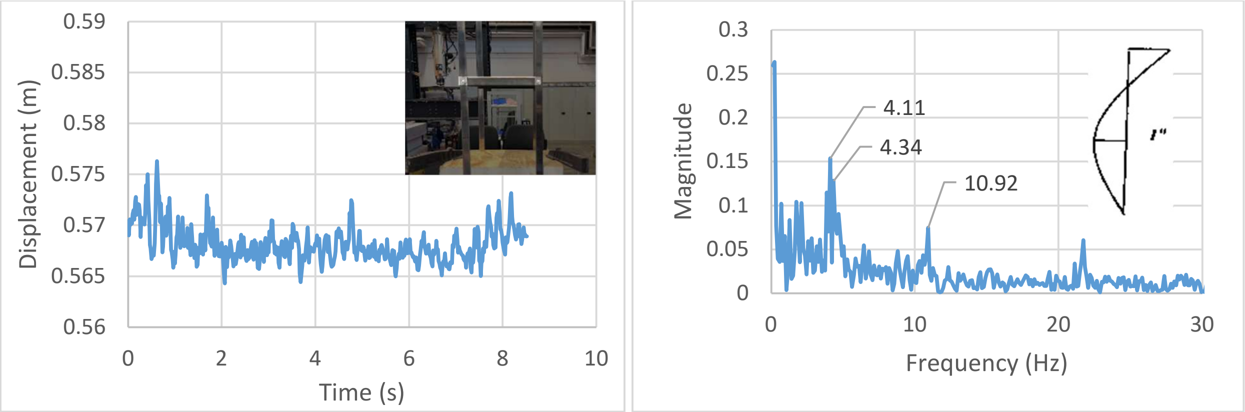


Figure 12. LiDAR measurement at 1st floor level with 2nd mode excited. Time series (left) and associated frequency spectrum (right).

Table 3. Comparison of first and second modal frequencies of a two-story frame model measured using contact and non-contact methods.

| Mode | Sensor | App | Post-processing | Frequency (Hz) |
|---|---|---|---|---|
| 1 | iPhone MEMS accelerometer | Vibration Analysis | In-app frequency spectrum | 4.35 |
| | Front-facing iPhone LiDAR (closest) | PhyPhox | FFT on exported time series data | 4.34 |
| 2 | iPhone MEMS accelerometer | Vibration Analysis | In-app frequency spectrum | 10.47 |
| | Front-facing iPhone LiDAR (closest) | PhyPhox | FFT on exported time series data | 10.92 |

The potential to measure the modal response of larger-amplitude vibrations is demonstrated by the second-mode frequency spectrum where both the first and second modal frequencies are clearly identifiable. Thus, if a patch could be reduced to a relatively small size, the iPhone LiDAR and PhyPhox app offer a method to very easily identify modal frequencies up to 30 Hz if a location on the structure is selected that is not an anti-node for any one mode. While the frequency spectrum currently requires a post-processing step, PhyPhox allows for development of experiments using a relatively simple XML schema, so a frequency spectrum based on a LiDAR signal can be coded in the future. This opens up a world of experiments on vibrating structures that have previously not been possible without very expensive equipment.

## *4. Noise characterization for close-range rear-facing iPhone LiDAR*

An attempt to measure the noise inherent in the LiDAR sensor was made by placing the phone at a distance of 0.25 m from a static target. PhyPhox was used to measure the distance and 4.3 minutes of distance measurements were collected at a sample rate of 60 Hz (Figure 13). Summary statistics are provided in Table 4, indicating the measurement of 0.250 m is accurate to within one millimeter when considering 3 standard deviations.

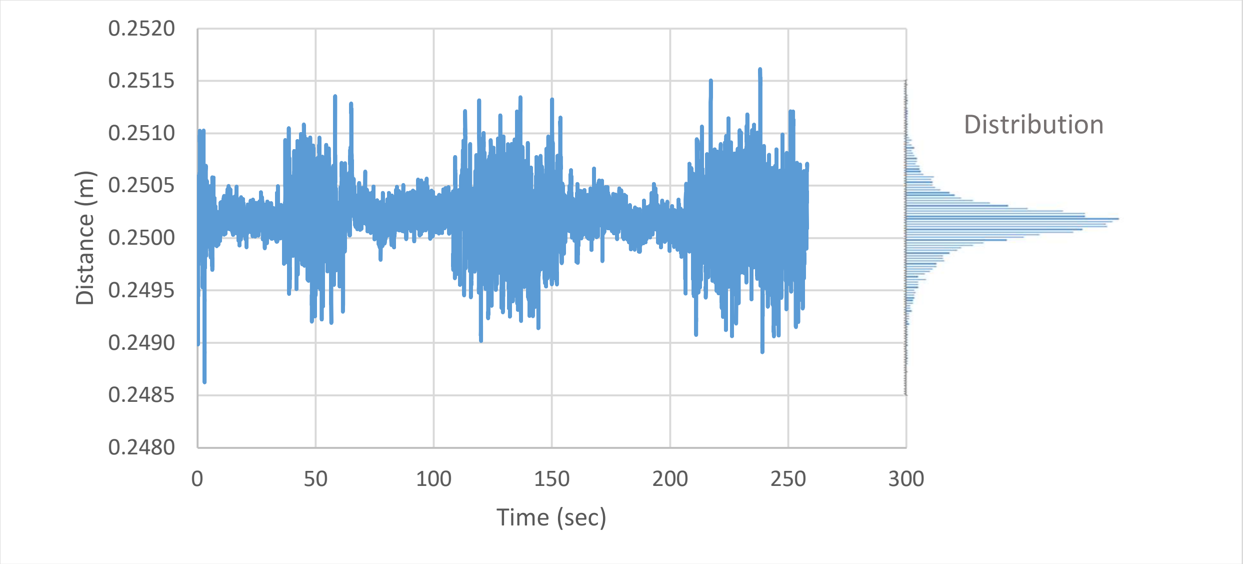


Figure 13. 4.3-minute time history of static LiDAR measurement at approximately 0.25 m.

Table 4. Summary statistics indicating measurement of 250mm ± 1 mm.

| Statistical Parameter | Value (m) | % of Mean |
|---|---|---|
| Median | 0.25019 | |
| Mean | 0.25018 | |
| Standard Deviation (s) | 0.00026 | |
| Maximum | 0.25162 | 100.575 |
| Minimum | 0.24863 | 99.380 |
| Range | 0.00299 | 1.195 |
| 1s = | 0.00026 | 0.103 |
| 3s = | 0.00077 | 0.309 |

The variations in Figure 13 appear to have two regimes. For example, there is tighter variation between 70 and 110 seconds and greater variation between 110 and 150 seconds. The source of this is unclear but could be related to background processor use. The variation of these regimes in time appears to be random.

Accurate measurements could not be obtained below 0.2 m or beyond 3 m and it appears that resolution of the measurements degrades with distance as would be expected for a sensing method based on time-of-flight principles. The LiDAR sensor has impressive sensitivity and accuracy at the lower end of its working range with a 3s error of 0.3%. The implications of this will be explored further in future work, with attempts to measure small amplitude vibrations. Based on this simple experiment, it appears the noise floor for the sensor is just below one millimeter, which is remarkably good for a device running a free app that many students will have in their pocket.

## Results and Discussion

In the experiments described above, the functioning of multiple sensors, apps, and post-processing methods have been demonstrated. The benefits and drawbacks of each sensor/method/app are summarized in Table 5.

The most important consideration for the sort of model one might use in a laboratory is the natural frequencies one would intend to measure. The greatest limiting factors for the tools explored here are the sample rate (or frame rate), the amplitude of vibration, and the distance from the phone to the vibrating object. The sensitivity for many physical demonstration models is adequate.

## Conclusion

This paper documented a series of experiments exploring the capability of phone-based measurement of vibrations. These experiments, employing contact and non-contact sensing, reinforce the growing body of research using phone-based acceleration sensing and demonstrate that non-contact methods employing the iPhone’s magnetometer, LiDAR sensor, and RGB camera. Purpose-built apps were explored in depth, like Vibration Analysis, with its robust frequency-domain analysis tools; Video Tachometer, with its creative use of the stroboscopic effect to identify frequency; and Video Physics, with its edge-tracking capability. The PhyPhox app, with its impressive and customizable suite of phone-based sensor experiments provided the platform for working with relatively new methods of non-contact sensing of vibrations, particularly the iPhone LiDAR sensor. The results showed that relatively precise and accurate natural frequencies can be identified using LiDAR for freely vibrating systems, particularly at closer distances (around 0.25 m), at fairly small amplitudes of vibration (as small as 1 mm), and below 30 Hz. The opportunity to use these tools to great effect in teaching-focused vibrations laboratories was demonstrated with measurements of tip-loaded and uniformly loaded cantilevers as well as a two-story frame model. Enormous potential exists for non-contact vibration measurement using phone-based LiDAR and other phone-based methods in teaching. If your students wonder if they can use their phones to learn, you should feel confident saying “yes, there’s an app for that.”

Table 5. Summary of sensor/method/app, calculation potential for various measures, limitations, and greatest value.

| **Sensor/Method/ App** | **Frequency** | **Position** | **Velocity** | **Acceleration** | **Limitations** | **Greatest Value** |
|---|---|---|---|---|---|---|
| LiDAR<br>(non-contact)<br>PhyPhox app | By FFT, cycle counting, or post-processing | Direct | By calculation | By calculation | 60 Hz sample rate, 30 Hz frequency of object, 5-m range, resolution better at close range (0.25m) and up to 3 m. | Direct measurement of displacement amplitudes on model or large structures within frequency limitations. |
| Magnetometer<br>(non-contact)<br>PhyPhox app | By FFT, cycle counting, or post-processing | - | - | - | 100Hz sampling, up to 50 Hz measurable. Low frequency applications. | Direct measurement of frequency of vibration of ferrous models without contact. |
| Stroboscope<br>(non-contact)<br>Video Tachometer app | Direct | - | - | - | 0.5-240 Hz | Non-contact measurement of frequency of vibration. |
| Feature Tracking in Video<br>(non-contact)<br>Video Physics app | By FFT, cycle counting, or post-processing | Can be scaled | Calculated in app | Not calculated in app | Limited by frame rate of 60 Hz | Demonstration of feature tracking. |
| Video Recording and Post-Processing<br>(non-contact)<br>Camera app | Direct period measurement | Direct, with scale used in the frame | By calculation | By calculation | Limited by frame rate of 60 Hz, or 240 Hz in “slo-mo” | Highly visual method of identifying natural period. |
| On-board MEMS Accelerometer<br>(contact)<br>Vibration Analysis and PhyPhox apps | By robust, app-based FFT | By app-based calculation | By app-based calculation | Direct | Up to 50 Hz, low noise floor (0.0005 g) | High precision and sensitivity when added mass effect is not an issue |
| High-Precision Accelerometer<br>(contact)<br>Vibration Analysis app and PCB Signal Conditioner | By robust, app-based FFT | By app-based calculation | By app-based calculation | Direct | High sensitivity (10V/g), up to 4000 Hz, very low noise floor (0.00001 g) | Highly accurate acceleration measurements across a wide range |

## References

[1] Riley, C. (2018, June). Teaching Modal Analysis with Mobile Devices. In 2018 ASEE Annual Conference & Exposition.

[2] L. D. Feisel and A. J. Rosa, "The Role of the Laboratory in Undergraduate Engineering Education," Journal of Engineeing Education 121-130, 2005.

[3] Mahoney, J. M., & Nathan, R. (2017, June), *Mechanical Vibrations Modal Analysis Project with Arduinos* Paper presented at 2017 ASEE Annual Conference & Exposition, Columbus, Ohio. 10.18260/1-2--28660

[4] Hopfner, H., & Morgenthal, G., & Schirmer, M. & Naujoks, M., & Halang, C. (2013) "On Measuring Mechanical Oscillations using Smartphone Sensors - Possibilities and Limitation," ACM SIGMOBILE Mobile Computing and Communications Review 1-11.

[5] Herrington, J., & Herrington, A., & Mantei, J., & Olney, I., & Ferry, B. (2009) *Using mobile technologies to develop new ways of teaching and learning* Murdoch Research Repository (Murdoch Research Repository) 1-14.

[6] Chopra, A.K. (2016) Dynamics of Structures, 5th Ed. Pearson.

[7] Clough, R. W., & Penzien, J. (2003). Dynamics of structures. Berkeley. CA: Computers & Structures.

[8] Prince, M. J., & Felder, R. M. (2006). Inductive teaching and learning methods: Definitions, comparisons, and research bases. Journal of engineering education, 95(2), 123-138.

[9] McDaniel, C., & Archer, G. (2009, June), *Developing A Feel For Structural Behavior* Paper presented at 2009 Annual Conference & Exposition, Austin, Texas. 10.18260/1-2--5095

[10] Facciolo, C. D., & Behrouzi, A. A. (2019). Interactive Physical Experiments in an Advanced Undergraduate Structural Dynamics Course. In 2019 ASEE Annual Conference & Exposition.

[11] Riley, C., Millar, J. D., Lozano, S., & St.Clair, S. (2016, June). Using Mobile Devices to Teach Structural Dynamics and Structural Health Monitoring. In 2016 ASEE Annual Conference & Exposition.

[12] “Apple LIDAR Demystified: SPAD, VCSEL, and Fusion…” Accessible at: https://4sense.medium.com/apple-lidar-demystified-spad-vcsel-and-fusion-aa9c3519d4cb

[13] PhyPhox, Your Smartphone is a Mobile Lab. Available: https://phyphox.org/ [Accessed 13-Feb-2023]

[14] Physics Toolbox. Available: https://www.vieyrasoftware.net/ [Accessed 13-Feb-2023]

[15] Kharutskiy, D. Vibration Analysis, 2014, Available: https://apps.apple.com/us/app/vibration-analysis/id817385888 [Accessed 13-Feb-2023]

[16] Kharutskiy, D. Video Tachometer, 2019, Available: https://apps.apple.com/us/app/video-tachometer/id1492583587 [Accessed 13-Feb-2023]

[17] Vernier. Video Physics, 2020. Available: https://apps.apple.com/us/app/vernier-video-physics/id389784247 [Accessed 13-Feb-2023]

[18] Gjelstrup, S.L. (2021) FFT Analysis: The Ultimate Guide to Frequency Analysis. Available: https://dewesoft.com/daq/guide-to-fft-analysis [Accessed 13-Feb-2023]