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Damage Detection of Identical Structures

Senior Project Spring 2019
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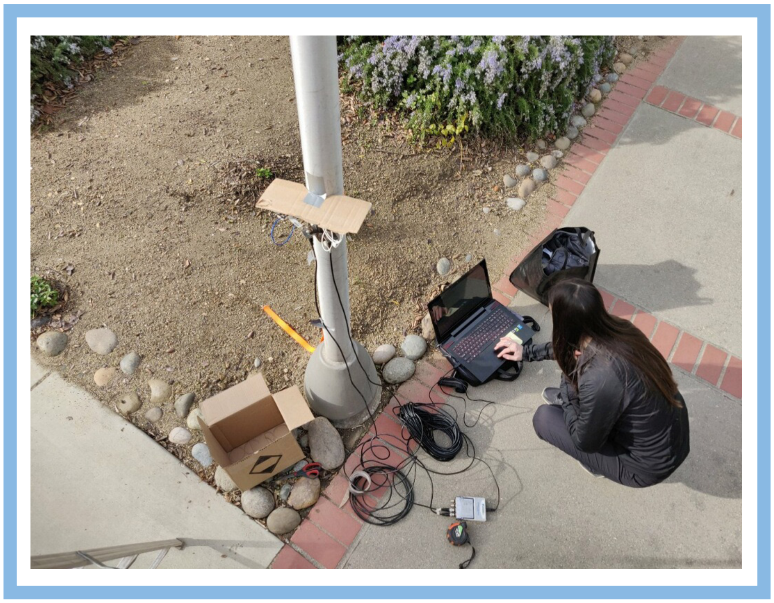
ABSTRACT

This study is concerned with measuring the vibrations of similar (and seemingly identical) structures, and attempting to detect damage in the structure by identifying outliers from the data. Furthermore, this study attempts to provide a logical conclusion surrounding the MPIT software by correlating each modal analysis program with MATLAB results from testing. Light poles around Cal Poly, San Luis Obispo are the subject of this study because the variability in structure among adjacent poles is hypothesized to be insignificant. A biaxial accelerometer device was mounted to each light pole and used to collect data. Initial tests were completed on six light poles in the ARCE courtyard to standardize the tests and begin to search for vibrational outliers, thereby detecting damage. From these initial tests, frequency alone was determined inconclusive for detecting damage in the light poles. Further data was gathered from taller light poles located on Highland Drive, San Luis Obispo, with the goal of finding and comparing damping ratios to identify damage. From these tests, we concluded that comparing damping ratio is an adequate method for detecting damage in light poles. We also concluded that the MPIT software is not reliable on it's own (without further hand calculations to provide a basis for understanding the results).



PROBLEM

The problem we wish to solve is whether or not structures can be investigated for damage through vibrations, both ambient and transient.

SOLUTION

We tested this by placing accelerometers on light poles and recording their frequencies and accelerations when no force was applied as well the damping ratio when we applied a force.

BACKGROUND/APPLICATIONS

UNIVERSAL SIGNIFICANCE

In Mexico, people are able to evaluate the height of water in wells by the vibrations and frequency the well emmits. This is important because water is a vital resource, and is necessary to those communities to survive. This provides us with a practical example of why comparisons of vibrational characteristics are important universally.

HYPOTHESIS

Prior to conducting testing on the structures, we theorized that both the frequency and damping ratio would be adequate methods of identifying damage. We came to this conclusion because when a light pole experiences damage (for example, from a considerable sudden impact, as was the case of this study), the vibrational characteristics might change and differ from those of the non damaged poles, therefore becoming an outlier in the data set.

CONTRIBUTION

These findings would greatly benefit society and retrofitting techniques if the conclusions are successful. If there is a simple way to evaluate whether structures need to be rehabilitated or torn down, such as comparing vibratory characteristics, we believe it would provide an easy method for evaluation. This could impact cities by identifying safe and unsafe light poles and similar simple structures around urban areas. Once a simple structure such as a traffic light or light poles downtown is damaged, this testing process may be able to conceptualize just how bad the damage is, and lead to enhancing retrofitting techniques for these types of structures.

PROJECT PRIORITIES

Step 1. Learn how to operate Signal Express and determine the meaning of acceleration and frequency graphs.

Step 2. Collect supplies and create an apparatus to hold the accelerometers.

Step 3. Configure software to run in two directions whether it be north/south and east/west directions or based on eccentricity.

Step 4. Conduct an interval test in order to find out which height above the ground to test the poles from and approximate their ambient frequency.

Step 5. Conduct analysis of multiple poles and look at accelerations and frequencies to see how they vary.

Step 6. Gather five minutes of data to run through the MPIT program.

Step 7. Conduct a damping ratio test on multiple poles, preferably a few that are not damaged and one that is.

Step 8. Create a matlab program to run the ambient data through and calculate damping ratio.

Step 9. Run data through MPIT to find damping ratio and identify modal analysis method that can be used in the future to test identical structures.

Step 10. Compare results and reflect upon findings.

LITERATURE SEARCH

Vamvoudakis-Stefanou, Kyriakos & Fassois, Spilios. (2014). Vibration-Based Damage Detection for a Population of Like Structures via a Multiple Model Framework.

The above article discusses a new framework to detect damage. Multiple experiments were conducted on a simple beam with various forms of damage to gather a “multiple model” (MM) framework. The authors argue that several models (rather than one) must be used on structures to adequately come to a conclusion about detecting damage. Even among seemingly identical structures, the variability of vibratory responses is too high to correctly detect damage. Furthermore, damage detection becomes much harder under low-impact damages. This study concludes that the MM format may provide better accuracy in the future, but is still insufficient to accurately quantify damage of any structure. We believe this article helps our study because it provides a rough procedure to testing similar structures, and quantifies that the results we collect may not conclusively relate to structures other than our given sample.

Keith Worden, David Allen, Hoon Sohn, Charles R. Farrar. Damage Detection In Mechanical Structures Using Extreme Value Statistics.

The article presents the theory that damage detection relies on identifying outliers from a standardized set of data points. All damage detection hypotheses stem from the theory that given a set of structures that behave relatively similar to one another, damage can be identified by finding those structures which behave drastically outside of the norm. This paper argues that this process may be misleading, since the control/ “normal” group may not accurately represent the population as a whole. We believe this article helps our study because is shows that if outliers are indeed found to exist in our light poles, that may not immediately identify damage and further investigations must be conducted.

Beskhyroun, S. (2011, April 14-16). Graphical Interface Toolbox for Modal Analysis.

This article attempts to explain the interface/program used in our experiment to find frequency peaks and damping ratios. The article identifies each method for modal analysis. The program inputs must be raw measured data, ideally ambient responses. The test parameters tab is explained, as well as the results tab and various graphical applications. To conclude, a sample modal analysis of a 3-story structure is included. This article helped us begin to understand how to interact with the interface and control some of the outputs from the software.

SIGNAL EXPRESS SETUP

Setup Steps:

1. Open DAQmx Acquire window
   Set Signal Input Range to 5 and -5
   Samples to Read: 20k for 10 seconds and 600k for 5 minutes
   Rate (Hz): 2k

Setting the signal input range focuses the program on collecting data between -5g and 5g. By changing the samples to read, we are able to collect any amount of data we desire. Changing the rate changes the interval of data we are collecting.

2. Open Filter window (configuration tab)
   Low Cutoff (Hz): 2,000
   High Cutoff (Hz): 30,000

Changing the cutoffs in the filter window allows us to focus on select modes. For this test we looked at modes 1 and 2.

3. Open Power Spectrum window (averaging tab)
   Averaging Mode: Vector Averaging
   Number of Averages: 10
   Weighting Mode: Exponential

By averaging the data we collected, we were able to throw out outliers in the data such as the first ten seconds of data. The accelerometers need time to warm up and they are very sensitive and may pick up signals that are not from our subject of interest. In order to average data from both accelerometer directions, we had to set the weighting mode to exponential rather than linear.

4. Tone Extraction window (advanced tab)
   Approximate Frequency (Hz): 5
   Search Range (% of sample rate): 0.25

We started by searching for the ambient frequency of the light poles by searching for a frequency around 5 hz with a larger search range, 0.25 hz. Once the ambient frequency was detected, we changed the approximate frequency to that of the ambient frequency and then decreased the search range in order to more closely measure vibrations around the resting frequency of the pole. This also allowed us to avoid picking up signals from other objects emitting frequencies in the surrounding area.

MODAL PARAMETERS IDENTIFICATION TOOLBOX (MPIT)

Setup Steps:

1. Open input file of desired light pole ambient accelerations
2. Change decimate order to reduce the amount of input data (the data was collected at 2048 hz for five minutes which ended up being too much information for the program to run)
3. Change filter to lowpass in order to look at frequencies in the first and second mode
   Filter order - 4
   F (hz) - 15
4. Change number of modes (located under System Identification) to 2
5. Change system order to 50 so that the program won't have to run through a surplus of unnecessary information
6. Calculate modal parameters
7. Go to Results tab and confirm that the modal frequencies are correct in order to find a modal analysis method that might be the best for determining an accurate damping ratio
8. Compare damping ratios from NExT/ERA, SSI, and SSI2 to see which comes closest to that of the Matlab values generated using logarithmic decrement

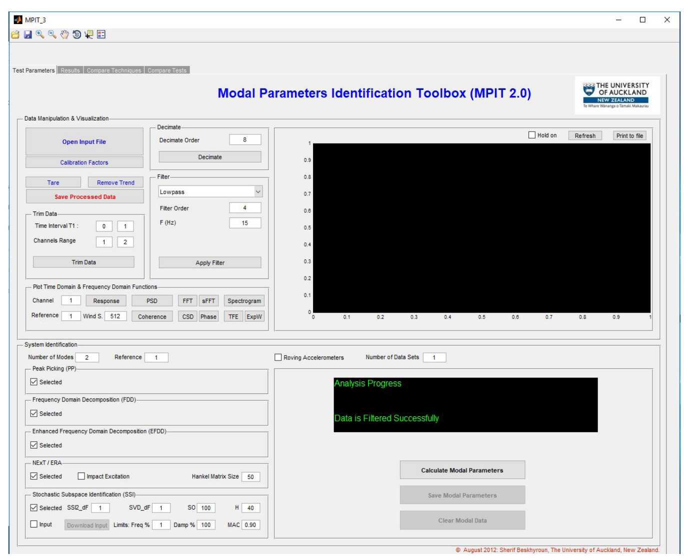
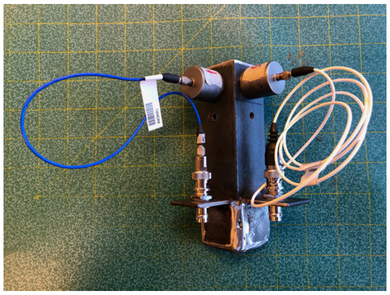


Fig 1. MPIT Main Page

Note: MPIT runs data in one direction so the data must be run in individual directions through the program as well to see if there is a difference in damping ratios for the cases in which we assume the accelerations run in the same direction and when they run in orthogonal directions as was the case in testing

CONSTRUCTION OF THE APPARATUS



After deciding to look at light poles as our subject of interest, we began by identifying possible testing apparatus' that would adequately collect the desired data. We needed the apparatus to be placed on poles with varying diameters. Our initial thought was to attach a device using magnets. However, this was deemed inadequate because the magnets may be susceptible to slipping under forced vibration and not all poles may be magnetic. We decided on a ratchet strap, which could be looped around the device and tightened around any size light pole. To ensure the accelerometers were mounted at exactly 90 degrees from one another, we used a steel angle with drilled holes to bolt the accelerometers securely in place. In order to connect the wires without moving the accelerometers and affecting the vibrations, we welded two smaller angles at the bottom of the apparatus so the wires would attach downwards without interference from testing. We debated connecting a shade to the apparatus to shield from the sun, but opted to simply use cardboard and duct tape directly to each light pole instead.

Fig 2. Construction of Apparatus

PROJECT SET UP

LIST OF EQUIPMENT:

Two accelerometers, Compass, Stopwatch, Apparatus, Ratchet strap, Cardboard, Duct Tape, Laptop, Extension cord

Fig 3. Setting up the Equipment

SETUP PROCESS:

For the length of this experiment, the accelerometers remained bolted in the apparatus. Once the desired height of the apparatus on the pole was found, we attached the steel angle with a ratchet strap, and tightened it into place. We used a phone compass to orient the device for the tests that were ran according to the North/South and East/West directions. Next, we twisted on both cords to the apparatus, and connected both cords to the Signal Express box which translates the data and sends it to the computer. We proceeded to attach a small piece of cardboard just above the device (so as not to interfere with the data collection) using duct tape, to shade the accelerometers from direct sunlight. Meanwhile, we opened Signal Express on the laptop and set all the parameters to our desired values for each given test. From here, we were ready to begin collecting data.

POLE LOCATIONS

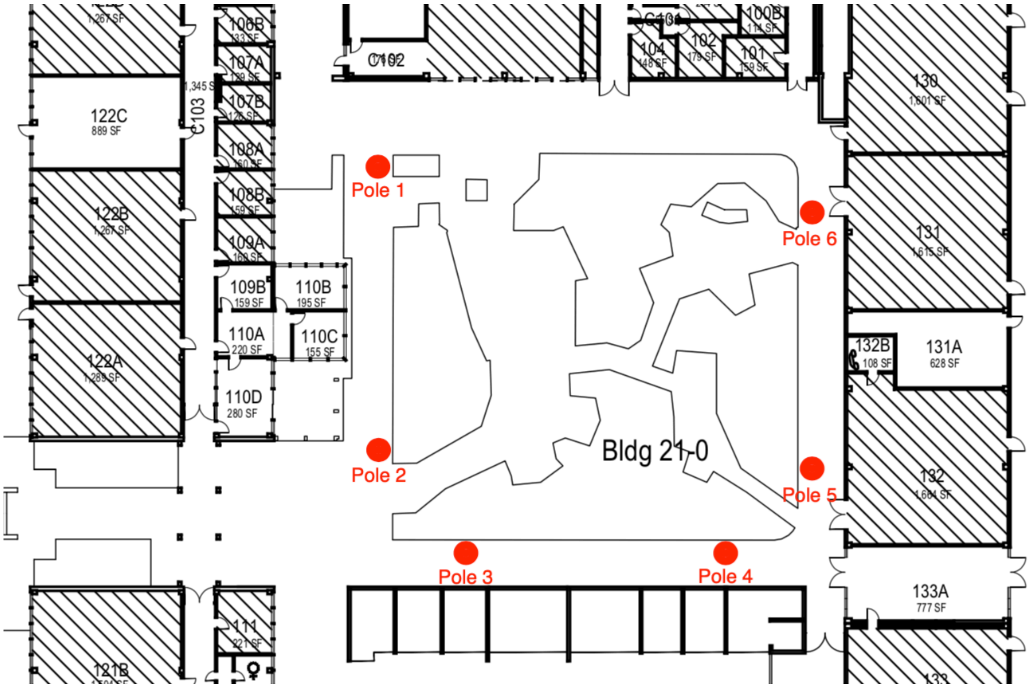


Fig 4. ARCE Courtyard (Building 21 - Engineering West)

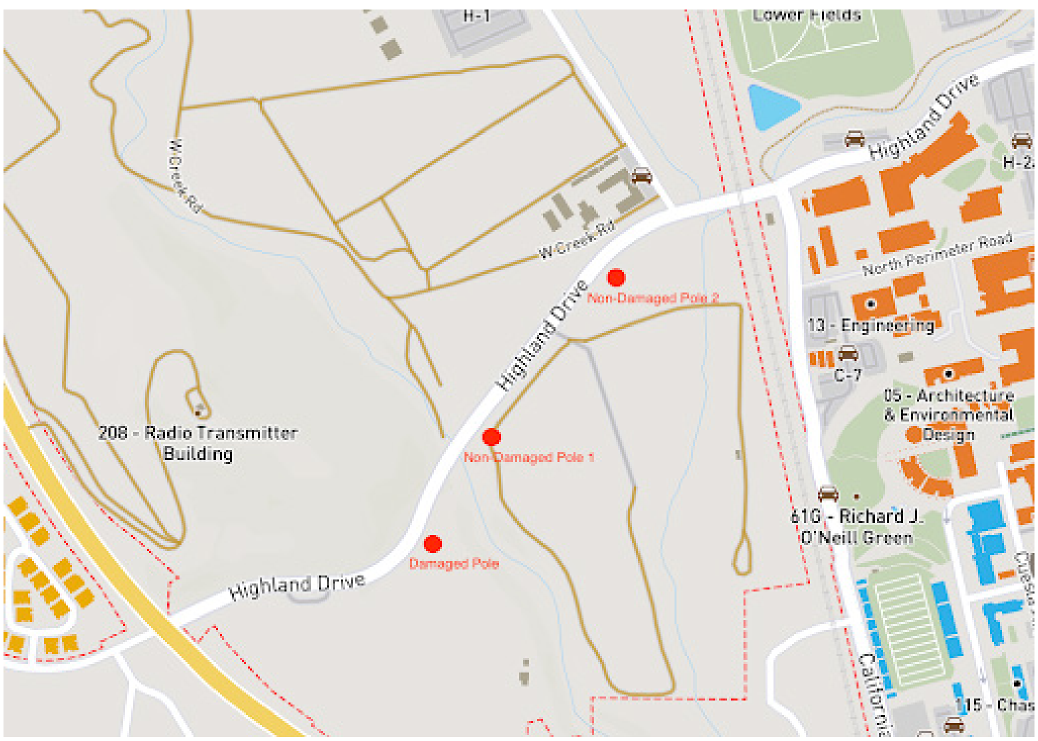


Fig 5. Highland Drive (Agriculture Area of Campus)

RESULTS: INCREMENT TEST

Location: ARCE Courtyard
Date and Time: February 12, 2019 at 9:00 am
Weather: 40 degrees, 84% humidity with 2 mph winds

When testing the ARCE Courtyard light poles, we wanted to first identify a location along the height of the pole that gave us the clearest results. On each pole in the courtyard, we attached the accelerometers at one foot increments and collected their accelerations and frequencies averaged over a period of 100 seconds. After comparing the results from each pole, we determined that testing the poles at size feet above ground level yields the clearest graphs. Looking at the Acceleration vs. Time graphs below, the graphs taken at 4 ft, 5 ft, and 7 ft have somewhat erratic wave shapes that are not as consistent as the graph at the 6 ft height. Similarly, when comparing the Frequency vs. Time graphs, the 6 ft height shows a much higher peak at the first mode, representing a larger amplitude. These were the results we were hoping to see and we used this height at all poles moving forward.

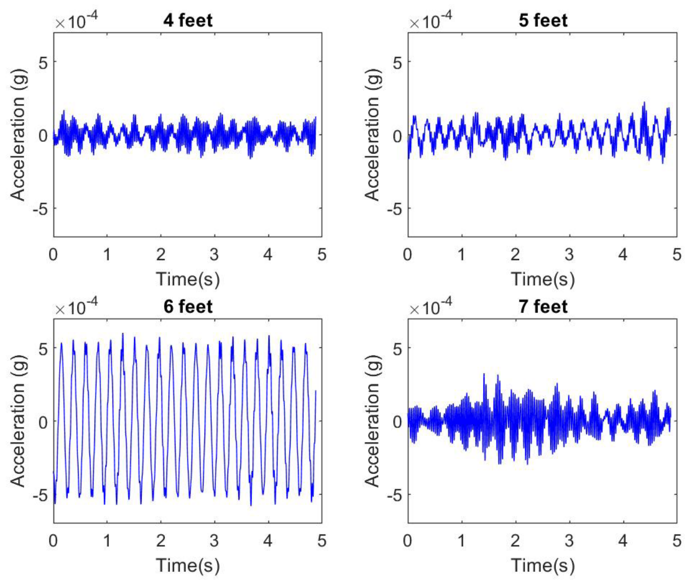


Fig 6. Time vs. Acceleration Graphs

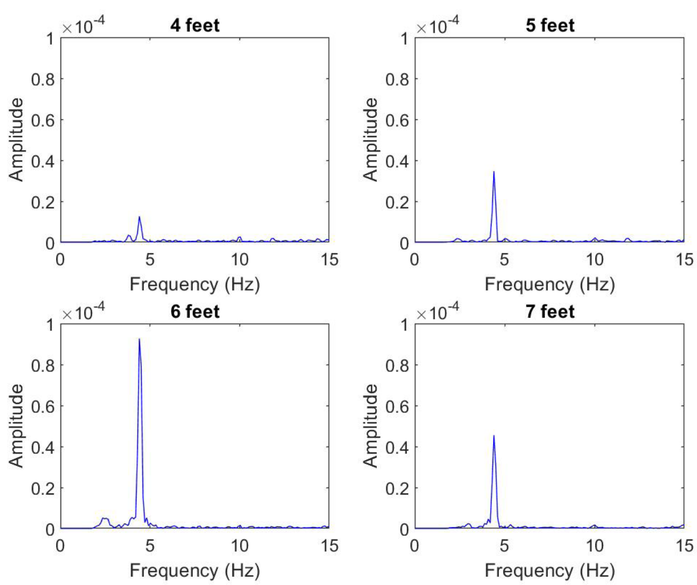


Fig 7. Frequency vs. Amplitude Graphs

RESULTS: MULTIPLE POLES COMPARISON TEST

Location: ARCE Courtyard
Date and Time: February 23, 2019 at 10:00 am
Weather: 56 degrees, 36% humidity with 2 mph winds

The multiple poles comparison test was used to determine if frequencies are a sound indicator for detecting damage in identical structures. We hypothesized that due to potentially weak soil conditions or sudden damaging impacts from the past, some of these poles may exhibit different frequency responses. We discovered that there is only a slight variation in frequencies of the poles in the ARCE courtyard, which is discussed in more detail below.

The Frequency vs. Amplitude graph shows that all poles experienced frequency peaks in the first two modes at around 2 and 4-4.5 Hz. Comparing the data from the table below, Poles 4 and 5 had slightly lower frequencies in the second mode than the other poles (3.99 and 3.79 Hz). However, after taking this into consideration, we determined that this discrepancy in the data was not enough to identify an outlier (a.k.a. detect damage). We were looking for a bigger difference in the data to identify damage accurately and almost all of the first mode frequencies were identical. Therefore, we concluded that either none of the six tested poles were significantly damaged, or frequency is not a valid indicator of damage. Regardless, further testing is required.

Pole	Frequency (hz)	
	Mode 1	Mode 2
1	2.05	4.40
2	2.05	4.55
3	2.05	4.40
4	2.05	3.99
5	2.15	3.79
6	2.05	4.51

Table 1. Multiple Poles Frequency Results

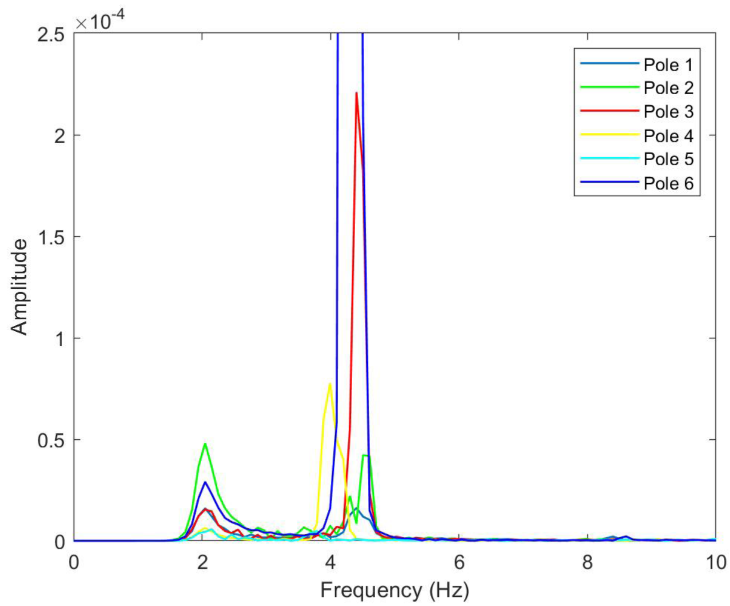


Fig 8. Frequency Comparison

RESULTS: DAMPING TEST

Location: Poles in AG Section of Campus (Have Overhang)
Date and Time: May 23, 2019 at 6:00 pm
Weather: 58 degrees, 80% humidity with 10 mph winds

The purpose of this test was to see if damping ratios in the light poles would show indication of damage in the structure. The subjects of this test were the taller light poles located on Highland Drive, San Luis Obispo. We conducted tests on three poles - two which appeared to have no significant damage and one which had been clearly damaged (likely as a result of a car crash). Other similar poles were identified along the opposite side of the street, but these were set in soil conditions rather than concrete sidewalk, and given our earlier testing on the ARCE Courtyard poles we elected not to test these poles.

For each light pole we conducted two tests. First, we collected acceleration vs. time data for a five minute sample of ambient vibrations. This would later be used in the MPIT program. Second, we physically shook each pole and collected the response for 30 seconds, again looking at acceleration vs. time. This would later be graphed in MATLAB and used to find the damping ratio through a function file shown below.

Figures 9-11 show each pole's response to shaking. Each graph is plotted to the same scale and ends after 12 seconds to show the damping curve more clearly. In each graph, the data points selected with a red star correlate to the coordinates we used when calculating damping ratio. This was relatively simple and accurate for the non-damaged poles (Figures 10 and 11) but the damaged pole experienced more erratic behavior. This made it difficult to select points from the graph to use for a damping ratio calculation. This is why in Figure 12, we selected 22 locations along the graph that we best identified as "peaks", providing us with a more averaged value of damping, and therefore a more accurate value.

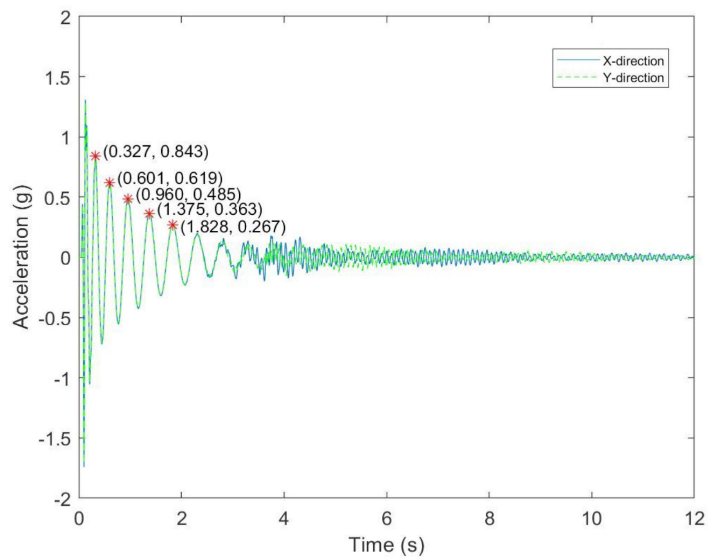


Fig 9. Non-damaged Pole 1 - Response to Excitation

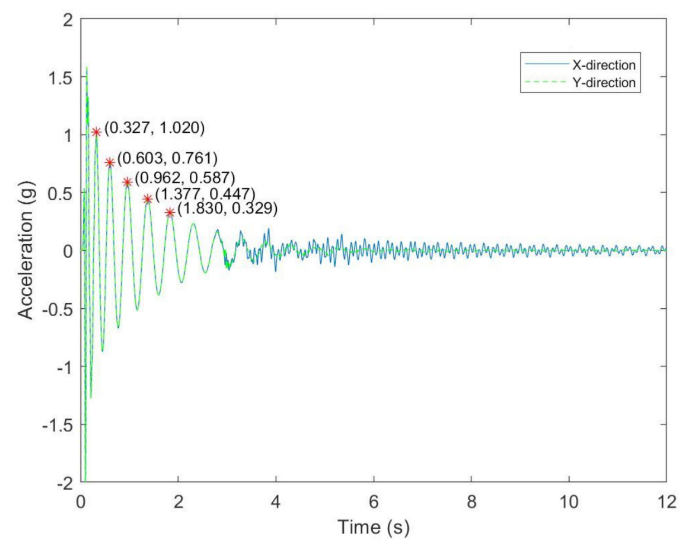


Fig 10. Non-damaged Pole 2 - Response to Excitation

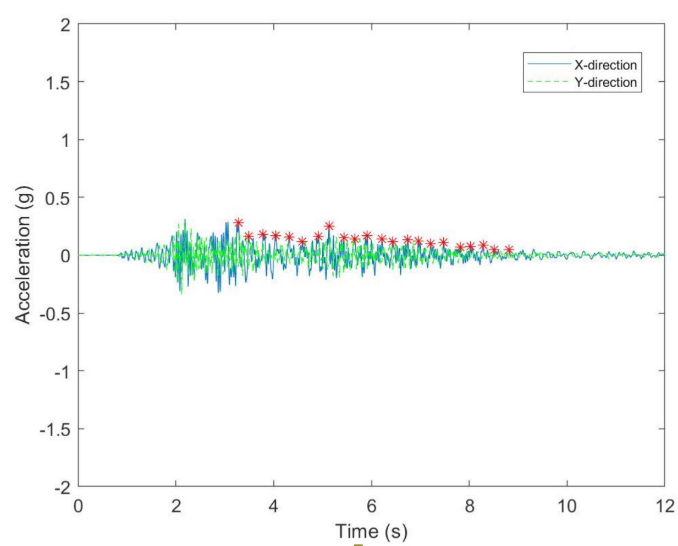


Fig 11. Damaged Pole - Response to Excitation

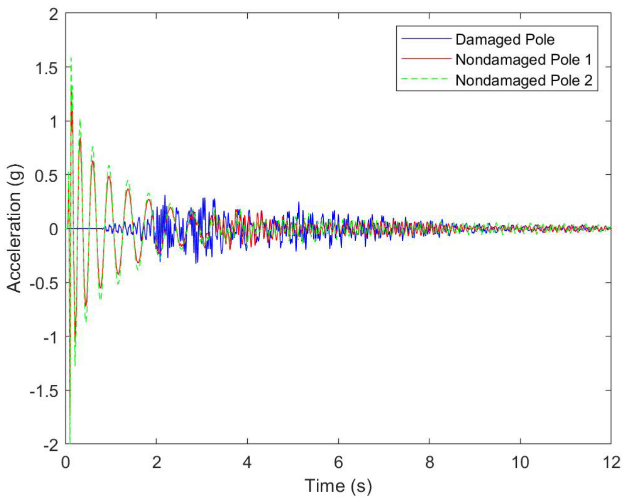


Fig 12. Response of 3 Poles - Single Direction

The following section of Matlab code is our function file that we used when calculating damping ratio. Function logDec inputs an array of any size with acceleration values at each peak. LogDec then calculates the damping ratio between each peak, stores these values, and averages each damping ratio. This setup proved useful because we could use this function to calculate a simple graph (both non-damaged poles), as well as the damaged pole which required more input parameters to gain a more accurate average.

```
function[z] = logDec(a)
%function logDec calculates an average damp-
ing ratio over multiple time steps
%logDec inputs an array of acceleration sca-
lar values
%logDec returns a single scalar value rep-
resenting the average damping ratio of the
data

    l = length(a);
    zSum = 0;
    for i = 1:(l-1)
            logDecrement = log(a(i)/a(i+1));
            zSum = zSum + logDecrement/
(sqrt(4*pi^2+logDecrement^2));
    end
    z = zSum/(l-1);
end

Outputs:
Damaged Pole:         1.31%
Nondamaged Pole 1:    4.58%
Nondamaged Pole 2:    4.50%
```

Fig 13. Matlab Function File - Logarithmic Decay Calculation

The table shown below compares the calculated values for damping ratio based on MPIT (all three modal analysis methods) and Matlab. The bolded values are our Matlab findings which we believe are the most accurate. We compared the values from the MPIT program to these Matlab values. For each light pole, the damping ratio closest to our MATLAB value is highlighted in green, and the value that is second closest is highlighted in yellow. As you can see below, the ERA method proved to be very close to the MATLAB values for both non-damaged poles. However, for the damaged pole, both SS1 and SS2 yielded the more accurate results. This led us to believe that different analysis programs will respond in different ways according to the structural characteristics of the member being tested.

Non Damaged Pole 1			
Program	NExT/ERA	SSI	SSI2
MPIT Decimate 4	7.69	15.26	15.74
MPIT Decimate 8	4.48	0.49	0.42
MPIT Decimate 16	2.86	3.56	3.40
MPIT Overhang Column @ 8	4.44	0.47	0.47
MPIT Orthogonal Column @ 8	3.50	0.16	0.16
Matlab	**4.58**	**4.58**	**4.58**

Non Damaged Pole 2			
Program	NExT/ERA	SSI	SSI2
MPIT Decimate 4	NA	NA	NA
MPIT Decimate 8	4.16	5.09	0.09
MPIT Decimate 16	2.64	7.45	2.36
MPIT Overhang Column @ 8	4.16	0.16	0.98
MPIT Orthogonal Column @ 8	5.10	0.50	0.50
Matlab	**4.50**	**4.50**	**4.50**

Damaged Pole			
Program	NExT/ERA	SSI	SSI2
MPIT Decimate 4	NA	NA	NA
MPIT Decimate 8	5.19	0.66	0.66
MPIT Decimate 16	1.99	2.18	0.36
MPIT Overhang Column @ 8	5.21	1.44	1.44
MPIT Orthogonal Column @ 8	4.60	7.00	2.20
Matlab	**1.31**	**1.31**	**1.31**

Table 2. Damping Ratios Comparison Chart

PAST AND FUTURE CONSIDERATIONS

Looking back on this experiment, we would have done a few things differently. Many of our challenges came from attempting to understand the MPIT program, as the literature was very limited and the coding behind the program was too complex to grasp. We would not advise using a program where the outputs cannot be trusted and understood fully. Another consideration we needed to keep in mind when testing relates to the eccentricity of the taller light poles. Since they have a large overhang on one axis, we chose to align the accelerometers according to these arbitrary axes. However, we discovered there may be a "principal axis" at some angle different than that of the axis we chose which could have provided us with clearer or different results. In addition, when testing the ARCE Courtyard light poles, we chose to place the accelerometers at a height of 6 ft because that yielded the clearest graphical results. This resulted in higher modal contributions from the second mode, as seen in the above graphs. We believe that an ideal location to identify first mode contributions would be attaching the device to the top of the pole. While this is virtually impossible for the tall poles on Highland Drive, we would have liked to conduct increment testing along those poles, possibly with a ladder to allow for testing capabilities further up the height of the poles.

CONCLUSION

In conclusion, we determined that comparing damping ratios of seemingly identical structures is an adequate method to detecting damage. However, this cannot apply to a broad range of structures, as our tests were limited to light poles which exhibit more simple characteristics than a more complex structure such as a building. For further light pole testing, we can confidently say that calculating damping ratios and comparing the data will accurately detect damage. We believe that more factors need to be controlled or accounted for when testing more complicated structures. For example, when testing columns in a building for damage, each column may be designed differently and likely attract load differently. Therefore, it may be hard to establish a large enough "control group" (a group of non-damaged elements to compare the outliers to) to yield accurate results. We also concluded that ambient frequencies are not likely an acceptable measure of detecting damage. Our findings from the ARCE Courtyard tests did not identify a significant outlier to warrant using similar frequency-based testing to further detect damage. This leads us to believe that even if a structure is damaged, the frequencies will remain similar to each other.

In regards to the MPIT software that we compared with out Matlab results, we can conclude that the results from this program should not be trusted. A simpler calculation to provide a reference to the MPIT program should be calculated first. This program is too complicated mathematically to fully understand which is why we recommend using it in addition to other methods.

REFERENCES

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Interface Toolbox for Modal Analysis.

Vamvoudakis-Stefanou, Kyriakos & Fassois, Spilios. (2014). Vibration-Based Damage Detection for a Population of Like Structures via a Multiple Model Framework.

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Special thanks to Graham Archer and Peter Laursen