CIAMTIS
U.S. DOT Region 3 University Transportation Center

CIAMTIS Lehigh Research Experience for Undergraduates (REU) Program – Year 4

October 4, 2023

Prepared by:
R. Sause, Lehigh University; C. Kusko, Lehigh University

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16. Abstract

Lehigh University, through its Institute for Cyber Physical Infrastructure and Energy (I-CPIE) and its Advanced Technology for Large Structural Systems (ATLSS) Engineering Research Center, in conjunction with the Pennsylvania Infrastructure Technology Alliance (PITA) program, conducted a virtual 10-week CIAMTIS Lehigh Research Experience for Undergraduates (REU) program. The program, which ran from June 1, 2022 through August 5, 2022, featured Lehigh University students who participated in a virtual program that exposed the students to a well-rounded experience, including both research-focused and professional development-focused activities. The program's activities included professional skills development workshops in addition to the assignment of students to an active CIAMTIS research project at ATLSS or a technical project related to the mission of CIAMTIS under the direction of the project Principal Investigator and graduate student mentor to help them navigate through the research project experience. The program culminated with a final report, presentation, and poster on their research findings.

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Introduction

BACKGROUND

Lehigh University, through its Institute for Cyber Physical Infrastructure and Energy (I-CPIE) and its Advanced Technology for Large Structural Systems (ATLSS) Engineering Research Center, in conjunction with Lehigh University's STEM Summer Institutes (STEM-SI) program, conducted a 10-week CIAMTIS Lehigh Research Experience for Undergraduates (REU) program. The program ran from June 1, 2022 through August 5, 2022. Lehigh University undergraduate students participated in the research-centric program, which exposed the students to a well-rounded professional development experience. Students were assigned to an active CIAMTIS research project at ATLSS or a research project that fit within the mission of CIAMTIS under the direction of the project Principal Investigator and graduate student mentor to help them navigate through the research project experience. Additionally, program activities included professional skills development workshops and trainings. The program culminated with a final report, presentation, and poster on their research findings.

OBJECTIVES

The objective of the REU program is to provide the students with a well-rounded professional development experience, featuring research as part of an active CIAMTIS research project at Lehigh University or a research project that fits withn the mission of CIAMTIS, and also including professional skills development workshops and seminars. This program exposed the students to research areas important to CIAMTIS while providing the students with research and professional development training that will prepare the students for future professional endeavors.

DATA AND DATA STRUCTURES

The participating students developed final reports, presentations, and posters. Copies of the final reports and posters are included within Appendix A of this final report.

CHAPTER 2

Methodology

INTRODUCTION

The REU program was conducted under the following criteria:

1. CIAMTIS Lehigh project principal investigators identified candidate students to participate in the Summer 2022 CIAMTIS Lehigh REU program. Additionally, an announcement regarding the STEM-SI program opportunities was distributed to Lehigh University undergraduate Civil and Environmental Engineering students for program consideration.

2. Recommendations and resumes were reviewed and interviews conducted, as necessary, in order to identify a candidate student for each active CIAMTIS Lehigh research project.

3. REU program dates were finalized as June 1, 2022 – August 5, 2022.

4. Students identified for the program were notified of their selection.

5. Principal Investigators and graduate student mentors were finalized for each project.

7. Program workshops and seminars were identified and scheduled.

8. Operation of the CIAMTIS Lehigh REU program, including workshops and project research, took place under the direction of the project Principal Investigator and project mentors.

9. Program participants completed final reports, posters, and formal presentations at the conclusion of the program.

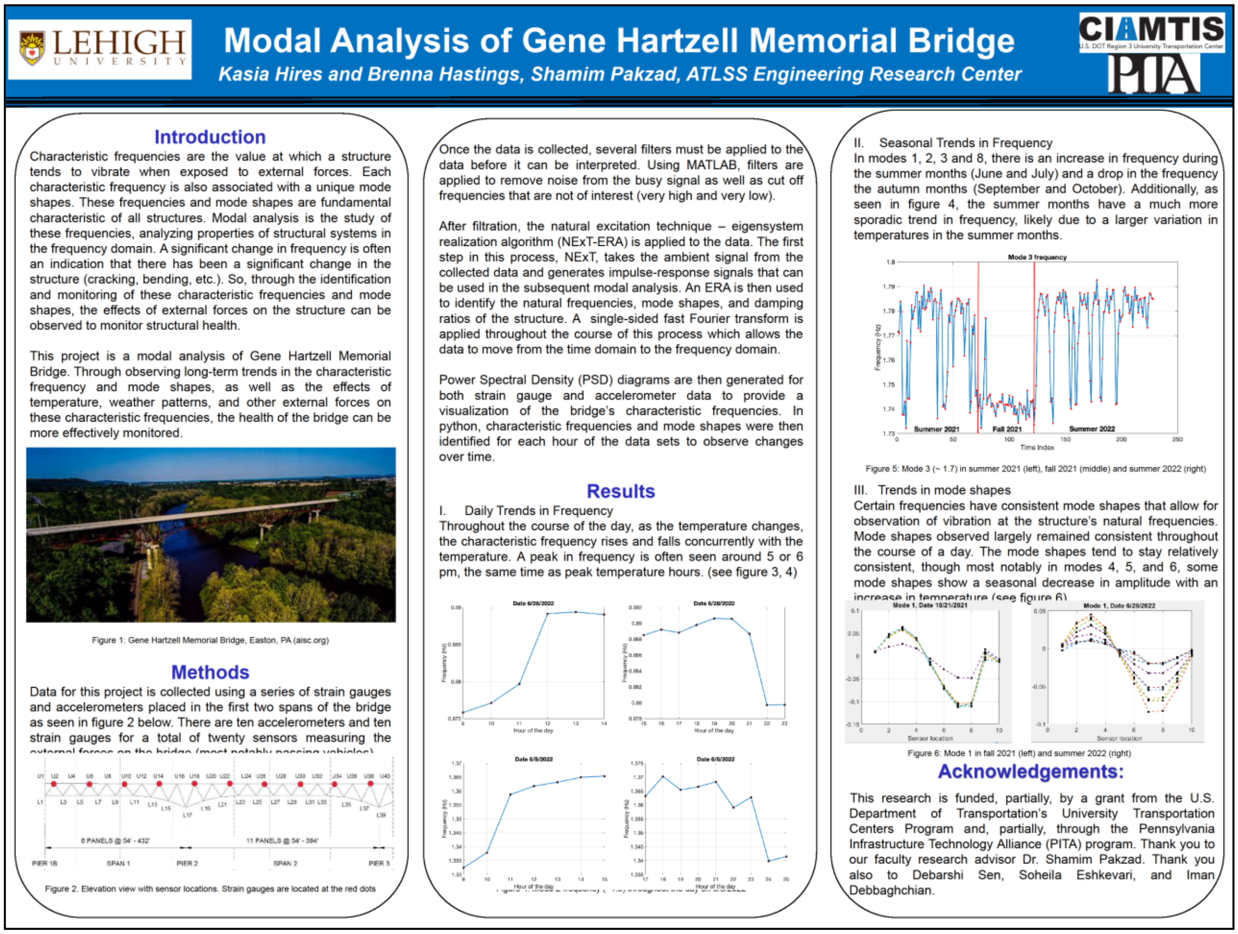
CHAPTER 3

Findings

The project matrix, along with particpating students, for the CIAMTIS Lehigh REU program is presented in Table 1. The results of this research were summarized in final project reports, which accompany this report in Appendix A, along with final posters, which are shown in Figures 1 and 2. Each student made a final program presentation to the project PIs prior to the conclusion of the program.

Table 1. Project, student, university, and faculty mentor matrix for the 2022 CIAMTIS Lehigh REU program.

CIAMTIS Project Title	**REU Student**	**University**	**Faculty Mentor**
Modal Analysis of Gene Hartzell Memorial Bridge	Brenna Hastings	Lehigh University	Shamim Pakzad
Modal Analysis of Gene Hartzell Memorial Bridge	Kasia Hires	Lehigh University	Shamim Pakzad
Non-Destructive Evaluation Methods	Alejandro Angeles Medina	Lehigh University	Ian Hodgson and Richard Sause



LEHIGH UNIVERSITY

Modal Analysis of Gene Hartzell Memorial Bridge

Kasia Hires and Brenna Hastings, Shamim Pakzad, ATLSS Engineering Research Center

CIAMTIS U.S. DOT Region 3 University Transportation Center

PITA

Introduction

Characteristic frequencies are the value at which a structure tends to vibrate when exposed to external forces. Each characteristic frequency is also associated with a unique mode shapes. These frequencies and mode shapes are fundamental characteristic of all structures. Modal analysis is the study of these frequencies, analyzing properties of structural systems in the frequency domain. A significant change in frequency is often an indication that there has been a significant change in the structure (cracking, bending, etc.). So, through the identification and monitoring of these characteristic frequencies and mode shapes, the effects of external forces on the structure can be observed to monitor structural health.

This project is a modal analysis of Gene Hartzell Memorial Bridge. Through observing long-term trends in the characteristic frequency and mode shapes, as well as the effects of temperature, weather patterns, and other external forces on these characteristic frequencies, the health of the bridge can be more effectively monitored.

Figure 1: Gene Hartzell Memorial Bridge, Easton, PA (aisc.org)

Methods

Data for this project is collected using a series of strain gauges and accelerometers placed in the first two spans of the bridge as seen in figure 2 below. There are ten accelerometers and ten strain gauges for a total of twenty sensors measuring the external forces on the bridge (most notably passing vehicles)

Figure 2. Elevation view with sensor locations. Strain gauges are located at the red dots

Once the data is collected, several filters must be applied to the data before it can be interpreted. Using MATLAB, filters are applied to remove noise from the busy signal as well as cut off frequencies that are not of interest (very high and very low).

After filtration, the natural excitation technique – eigensystem realization algorithm (NExT-ERA) is applied to the data. The first step in this process, NExT, takes the ambient signal from the collected data and generates impulse-response signals that can be used in the subsequent modal analysis. An ERA is then used to identify the natural frequencies, mode shapes, and damping ratios of the structure. A single-sided fast Fourier transform is applied throughout the course of this process which allows the data to move from the time domain to the frequency domain.

Power Spectral Density (PSD) diagrams are then generated for both strain gauge and accelerometer data to provide a visualization of the bridge's characteristic frequencies. In python, characteristic frequencies and mode shapes were then identified for each hour of the data sets to observe changes over time.

Results

I. Daily Trends in Frequency

Throughout the course of the day, as the temperature changes, the characteristic frequency rises and falls concurrently with the temperature. A peak in frequency is often seen around 5 or 6 pm, the same time as peak temperature hours. (see figure 3, 4)

II. Seasonal Trends in Frequency

In modes 1, 2, 3 and 8, there is an increase in frequency during the summer months (June and July) and a drop in the frequency the autumn months (September and October). Additionally, as seen in figure 4, the summer months have a much more sporadic trend in frequency, likely due to a larger variation in temperatures in the summer months.

Figure 5: Mode 3 (~ 1.7) in summer 2021 (left), fall 2021 (middle) and summer 2022 (right)

III. Trends in mode shapes

Certain frequencies have consistent mode shapes that allow for observation of vibration at the structure's natural frequencies. Mode shapes observed largely remained consistent throughout the course of a day. The mode shapes tend to stay relatively consistent, though most notably in modes 4, 5, and 6, some mode shapes show a seasonal decrease in amplitude with an increase in temperature (see figure 6)

Figure 6: Mode 1 in fall 2021 (left) and summer 2022 (right)

Acknowgements:

This research is funded, partially, by a grant from the U.S. Department of Transportation's University Transportation Centers Program and, partially, through the Pennsylvania Infrastructure Technology Alliance (PITA) program. Thank you to our faculty research advisor Dr. Shamim Pakzad. Thank you also to Debarshi Sen, Soheila Eshkevari, and Iman Debbaghchian.

Figure 1. Project poster for CIAMTIS project titled *Modal Analysis of Gene Hartzell Memorial Bridge.*

Non-Destructive Evaluation Methods

A. Angeles, I. Hodgson, R. Sause, CIAMTIS REU

WHAT IS NDE?

Non-Destructive evaluation (NDE) methods are used to assess flaws in steel structures, and in particular, in-service steel bridges. There are several NDE methods commonly used on bridges, which are used to search for and detect potential flaws, characterize them, and perform flaw sizing. There are two categories of NDE methods. There are both external (surface) and internal (subsurface) methods. All bridges in the United States must be inspected every 2 years per federal guidelines and the method most routinely used is Visual Testing. However, additional NDE Methods are used to confirm these visual inspections in cases of cracks that are difficult to see or for cracks that cannot be seen (internal cracks).

LAB WORK

Dye-Penetrant (PT) Testing was used on laboratory fatigue test specimens to assess the reliability of PT testing in identifying the crack tip by opening cracked specimens and examining the crack surface.

Dye Penetrant Testing

Source: https://www.codesteel.com/wp-content/uploads/2021/09/unnamed-1.jpg

WHY IS IT NEEDED?

Offering cost-effectiveness, NDE methods are simple to execute and take no time at all. With the methods requiring different levels of expertise, these methods offer a quick but safe way of inspecting a material (in this case steel) without affecting the material in any way. An obvious benefit is the identification of defects that, if they were to remain undetected could result in catastrophic failure. The use of these NDE methods incurs cost but if used effectively they can increase the reliability of the structure and potentially reduce maintenance costs over the life of the structure.

Source: commercialappeal.com

BACKGROUND

Of 617,000 accounted bridges in the US, about 42% of those bridges are at least 50 years old, and 7.5% of them are considered structurally deficient. Out of all the bridges, around 33% are steel bridges. These bridges are federally mandated to be inspected every 2 years. Non-destructive Methods allow for confirmation and/or detection of defects that develop over time such as surface cracks, embedded cracks, weld defects like lack of fusion, porosity, etc. The use of these NDE methods incurs cost but if used effectively, they will be the cause of considerable financial savings.

PROJECT FOCUS

The focus of the project was on the external (surface) methods such as Visual Inspection Testing, Dye Penetrant Testing (PT), Magnetic Particle Testing (MT), and Eddy Current Testing (ET). Understanding the uses, equipment, surface preparation, procedure, interpretation of results, and applications of each method.

FUTURE NDE TECHNOLOGIES

Current Non-Destructive Evaluation Methods are are effective in certain situations but there are promising emerging technologies that can greatly change the way bridges are inspected. These technologies can provide more data in a more time-efficient and cost-effective manner. Some examples include drone inspection, piezoelectric paint, Unmanned Aerial Vehicles (UAVs) etc.

Source: mntransportationresearch.org

SUMMARY

Allowing for early detection, NDT methods have proven to save time and money. With the right application and use, these methods are cost-effective and improve the reliability and extend the service life of these structures. NDT methods allow bridge inspectors and engineers to quickly act after a flaw is assessed and characterized as a defect. The funding and research of new and improved methods will help make the inspection of in-service steel bridges safer and simpler. Methods such as UAVs show promising results in improving safety, traffic prevention, and data collection. Ensuring the safety of inspection personnel and the motoring public during bridge inspection is critical. These new technologies have the potential to limit the negative impacts that can result from lane closures and costly bridge access equipment.

Source: weldingandndt.com

PITA

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Acknowledgement(s):

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LEHIGH UNIVERSITY

Figure 2. Project poster for CIAMTIS project titled *Non-Destructive Evaluation Methods*.

The REU Program

Beyond the research project, the students engaged in various professional development activities throughout the duration of the 10-week program, as outlined below:

- Orientation and Training sessions:
    - Program orientation integrated with Lehigh University's STEM-SI Research Experience for Undergraduates program and focused on :
        - Laboratory Safety, by Randy Shebby, Assistant Director, Department of Environmental Health and Safety, Lehigh University
        - Research Ethics, by Neal Simon, Professor, Biological Sciences, and Vassie Ware, Professor, Biological Sciences, Lehigh University
    - Technical report writing presentation
    - Tutorial on Library Resources and Research, prepared by Philip Hewitt, Engineering and Electronic Collections Librarian, Lehigh University
- Professional development sessions:
    - *Career Exploration and Decision Making* by Andrea Reger, Associate Director, Career Services, Lehigh University
    - *Resume & Cover Letter Lab* by Lisa Kller, Associate Director, Career Services, Lehigh University
    - *How to Conduct an Effective Internship or Job Search & Building Your Professional Network* by Ali Erk, Associate Director, Graduate Student Career Development, Lehigh University
    - *Successful Interviewing* by Bill Burden, Associate Director, Graduate Student Career Development, Lehigh University
    - *Graduate School Admissions and Graduate School Preparation and Expectations* by Lehigh University faculty and gradudate school alumni
- Weekly community development research seminars by Lehigh University faculty
- Weekly morning cafe group discussions
- Research activities:
    - Students worked on their respective CIAMTIS-focused projects
- Final Presentations:
    - Students made 15-minute final presentations with accompanying question and answer session.
- Final Poster :
    - Students create poster and present to fellow students and alumni judges as part of STEM-SI Research Day expo at Lehigh University.

CHAPTER 4

Recommendations

Future REU Program

Participating REU students were provided with a well-rounded professional development experience that focused on conducting research as part of active CIAMTIS research projects at Lehigh University under the direction of project PIs and mentors. Three participating REU students also engaged in training and orientation sessions, professional development sessions, seminars, and research group activities focused on enhancing the students' overall professional skills and exposure.

Lehigh's CIAMTIS administration plans on continuing the REU program in the Summer of 2023.

Appendix A

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Non-destructive Evaluation Methods

August, 2022

Prepared by:
A. Angeles,
Lehigh University

PennState College of Engineering
LARSON TRANSPORTATION INSTITUTE

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	14. Sponsoring Agency Code

15. Supplementary Notes

[Enter sponsor contact's Name, Email, Phone]

16. Abstract

Non-Destructive (NDE) methods play a vital role in helping to assess in-service steel bridges for flaws that put the integrity of the structure at risk of failure. This report covers NDE methods
that pose a threat

17. Key Words Non-Destructive Evaluation Methods, steel bridges, Non-Destructive Testing, Future Non-Destructive Evaluation Methods	**18. Distribution Statement** No restrictions. This document is available from the National Technical Information Service, Springfield, VA 22161

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CHAPTER 1

Introduction

Background

The project is related to fatigue of welded steel bridges. Highway bridges are subjected to millions of stress cycles during their lifetime, caused by heavy trucks and vibration. If the cyclic stresses are excessive, cracks can develop at welds. We will be performing full-scale tests of steel components involving cyclic loading with the goal of producing a crack that we can study. We'll be looking at the accuracy of inspection techniques used to find the cracks. Inspection for cracks is an important task that bridge owners must perform regularly on bridges in service. I took a look deeper into the various methods that have the capability of identifying fatigue cracks.

Project Objectives

Gain an understanding of Non-destructive (NDE) Methods specifically the exterior (surface) methods. Learn how each method works as well as how one decides which method to apply. Determine the disadvantages and the limitations of each method. Look into what happens after a flaw is detected using NDE. Investigate developing new methods that are relatively new and are undergoing research.

Research Approach

My focus was on the exterior (surface) NDE methods. This includes Dye Penetrant Testing (PT), Magnetic Particle Testing (MT), and Eddy Current Testing (ET). Understand the uses, equipment, surface preparation, procedure, interpretation of results, and applications of each method.

CHAPTER 2

What Are Non-Destructive Evaluation Methods

What Are Non-Destructive Evaluation Methods

Non Destructive Evaluation Methods are used to detect and assess flaws. All bridges in the United States must be inspected every 2 years per federal guidelines and the method most routinely used is Visual Testing. Therefore, NDE Methods are most commonly used to confirm these visual inspections for cracks that are difficult to see or for cracks that can not be found (internal cracks).

Dye Penetrant Testing

Dye Penetrant Testing (PT) is a simple inexpensive method that helps provide initial detection of flaws and confirmation of visual inspections. After the test surface is cleaned with a cleaner, then a penetrant is applied. This penetrant contains a red-colored pigment in a thin oil which allows it to flow into surface defects by capillary action. After a holding period, excess penetrant is wiped from the surface. Afterward, the developer is applied as a thin spray-on film, which deposits a white powdery layer over the test area. The developer extracts penetrant residing in cracks, providing a colored indication of those flaws. Soon after, the test surface is visually inspected with the test highlighting the presence, length, and width of the flaw.

Some disadvantages include the method not being suitable for inspecting the elements with a porous surface. It requires caution in pre-cleaning, chemical handling, and removal of excess penetrant. Proper access to test components is required to safely conduct the inspection. The process is time-consuming and may not be cost-effective where multiple locations need to be inspected.

Figure 1. Example of dye penetrant test highlighting crack in test piece

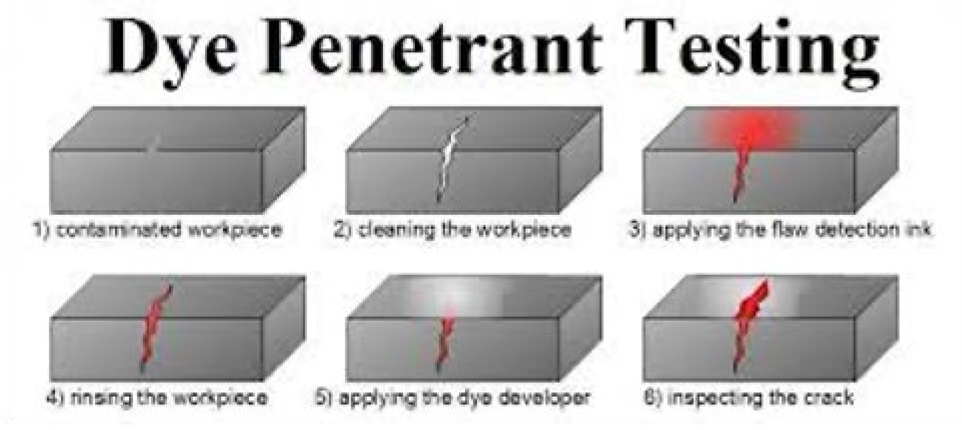


Figure 2. Dye penetrant step by step process involving cleaner, penetrant, and developer

Magnetic Particle Testing

Magnetic Particle Testing (MT) can be used to detect surface and near-surface internal flaws and confirmation of visual inspections. When Powered, permanent magnets and yokes create magnetic fields in steel bridge components between the poles of the magnets or poles created by the legs of a yoke. This generates lines of magnetic flux running between magnets or the legs of a yoke. Any flaw that cuts those lines of flux will create a localized area of flux leakage. The flaw will not support as great of a magnetic field as the surrounding steel, which causes the magnetic field to spread out and leak out of the test piece.

Consequently, iron particles are attracted to and cluster to these magnetic leakage sites. The greatest amount of flux leakage occurs when the flaw is perpendicular to the lines of flux.

Some disadvantages to note include irregular surface finishes, the need for lane closure for performing the test, and the non-applicability of non-ferromagnetic material. The coating must be 2 mils which is 2 thousands of an inch or less.

Figure 3. Magnetic yoke being used to perform MT

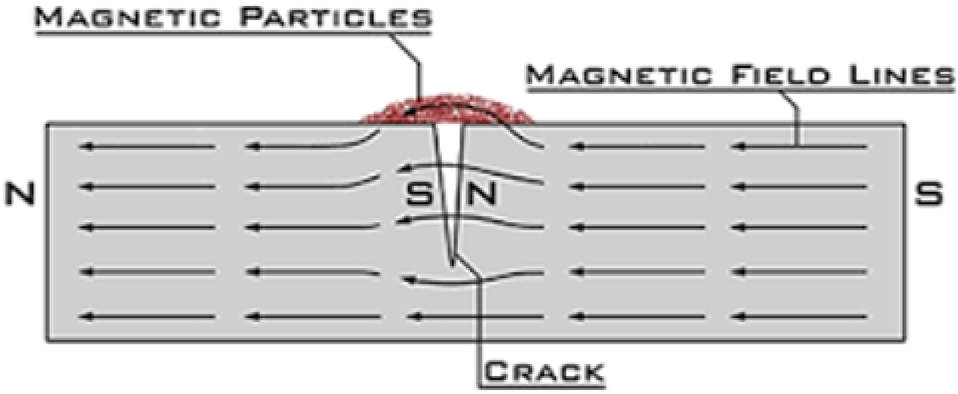


Figure 4. Diagram showing flux lines going a crack

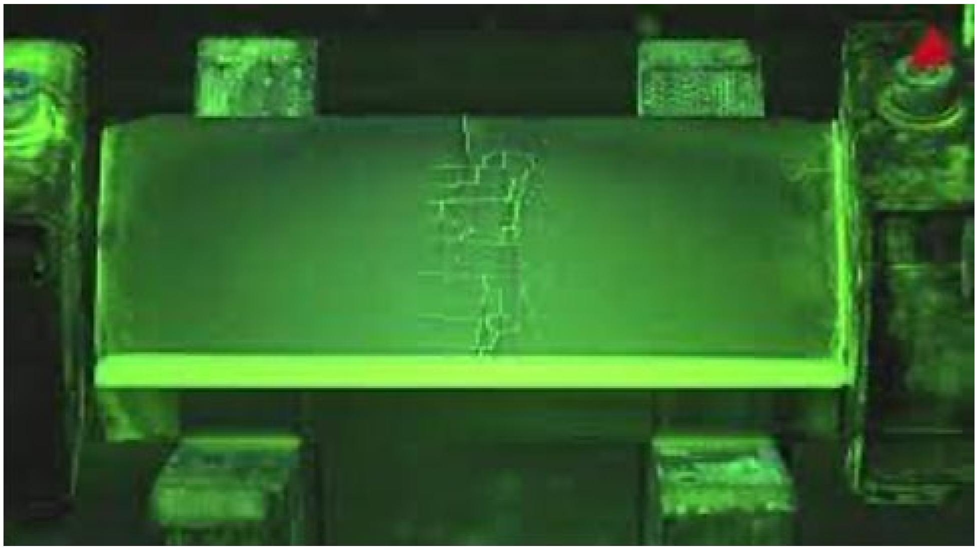


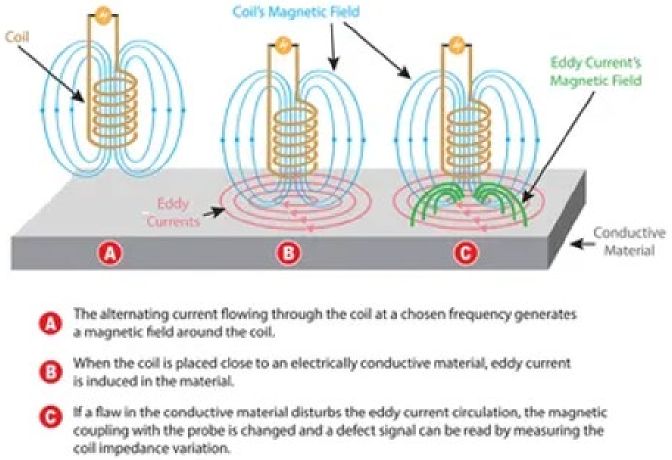
Figure 5. Sample specimen under ultraviolet light to highlight iron particles clustering in flux leakage sites

Eddy Current Testing

Eddy Current Testing (ET) is an emerging NDE method for bridge applications and is used mainly for surface and near-surface flaw detection. The ET flaw detector creates an AC current in the probe containing a wound wire coil (the primary coil). When the probe is placed on the test piece, the current creates a dynamic magnetic field about the probe that will create circular eddy currents in a test piece centered on the probe. Flaws transverse to the circular movement of the eddy currents disturb the induced magnetic field and impact the current flow in the probe, which provides a means for detection in flaw detector electronics.

In other words, the magnetic field produces eddy currents in the test piece centered on the probe. The currents induced on the test piece oscillate in a circular pattern and flow in a direction opposite to the current in the coil. The eddy current generates a specific magnitude and phase, so any cracks or discontinuities that disrupt the magnitude and phase are easily identifiable.

Some disadvantages include that the signals from the eddy current method can be affected and distorted by factors such as lift-off (distance between the test coil and the specimen), electrical conductivity, magnetic permeability, inhomogeneity of the material, or the thickness of the test.
For flaw location, an ET flaw detector, an eddy scope, is used, which contains an impendence plane screener on the test unit that lets the operator view the effect of the imposed magnetic field of the probe interacting with the induced field in the test piece.



A The alternating current flowing through the coil at a chosen frequency generates a magnetic field around the coil.

B When the coil is placed close to an electrically conductive material, eddy current is induced in the material.

C If a flaw in the conductive material disturbs the eddy current circulation, the magnetic coupling with the probe is changed and a defect signal can be read by measuring the coil impedance variation.

Figure 6. Diagram showing the application of the eddy current probe on a material and the corresponding magnetic fields induced

Figure 7. ET flaw detector used to test weld toe of steel specimen

What Happens If A Flaw Is Detected

NDE methods are used to identify flaws. There are various types of indicators that there is a flaw present as previously mentioned. When analyzing and attempting to interpret the test results of any NDE method, operators can make 2 types of errors. Type 1 error is where the operator misses a flaw or does not properly interpret an indication as being related to a flaw. This is termed an undercall. Type 2 error is where the operator misinterprets an anomalous indication as a flaw, termed an overcall. The Flaw must then be sized and characterized for future reference.

Flaw Sizing

A flaw needs to be sized and its location recorded properly after detection. The process of properly recording a flaw involves taking measurements, and photographs, marking the bridge component, and preparing a sketch showing the location, size, and orientation of a flaw. Where fatigue is a concern, the tips of surface-breaking cracks must be marked using a punch or indelible ink pen as well as the date the mark was made.

Flaw Characterization

After detection, follow-up action is required to determine the criticality of a flaw. An unacceptable flaw is considered a defect either when it falls outside of specifications or when it is anticipated that it would cause steel bridge components to fail in service. A factor to take into consideration is the potential impact that the flaw has on a structure. The nature of the flaw, the component in which the flaw is located, and the potential of that component's fracture on the structural integrity of the bridge is how the impact and criticality of flaw is determined. The potential threat that a flaw has on a bridge's structural integrity depends on its size, type, disposition in a structural component, type of steel involved, the impacted structural details, and the magnitude and nature of loading (both live and dead loads). Flaw severity can be ranked from least to worst as porosity, slag strings, arc strikes, lack of penetration, lack of fusion, and cracks. Characterization of flaws by type can be done readily for surface-breaking flaws. Subsurface flaws can be best characterized by type using radiography. It is easier to characterize a flaw by size than by type.

CHAPTER 3

Future Non-Destructive Evaluation Methods

Future of Non-Destructive Evaluation Methods

NDE methods are simple yet inexpensive methods but they are always improving. Following are some of the developing new technologies.

Piezoelectric Paint

A very new NDT method, smart paint uses microencapsulated dyes that outline fatigue cracks as the crack forms and propagates. The paint contains a small resin layer that conducts electricity, and electrodes are attached to measure the depth and size of a crack. This method will enable engineers to monitor vibrations throughout the lifetime of a structure, allowing for accurate predictions of when fatigue will become a problem.

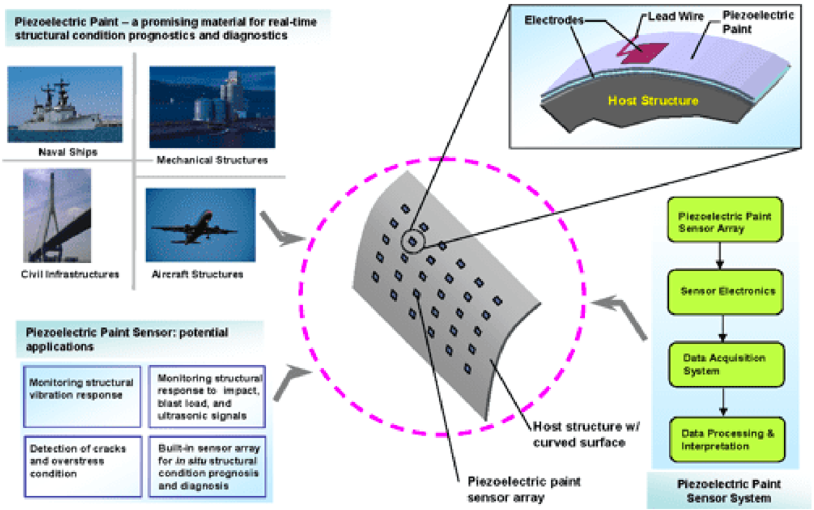


Figure 8. Diagram showing sensor array and applications

Phased Array Ultrasonic Testing (PAUT)

Phased array ultrasonic flaw detectors perform advanced forms of ultrasonic imaging known as phased array ultrasonic testing (PAUT). This method employs sensors that contain many small electronic transducers in arrays (a row or column) that are pulsed sequentially to establish a pattern of constructive waves at several angles, allowing a sensor to sweep the area without manipulating it. Test data are stored digitally in the flaw detector and can be subsequently viewed in conventional A and B scan modes as well as the sector (S scan) mode. Other probes are available that enable PAUT to detect corrosion damage (loss-of-section).

PAUT testing provides better imaging and image processing resulting in better, quicker characterization and sizing of flaws. PAUT allows the operator to access more UT information from the weld and easily locate any flaws based on the depth of the test piece and the surface distance between the flaw and the transducer.

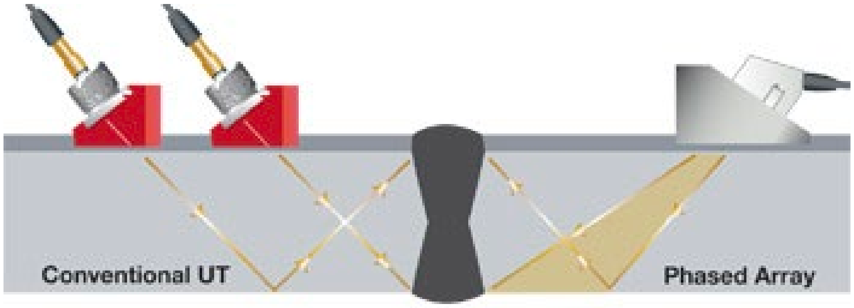


Figure 9. Diagram showing the contrast between conventional UT and phased array

Non-Destructive Evaluation Methods Using Unmanned Aerial Vehicles

Unmanned Aerial Vehicles (UAVs) have been gaining momentum for bridge monitoring in recent years, particularly due to enhanced accessibility and cost efficiency, deterrence of traffic closure, and improved safety during an inspection. These UAVs come in three different designs: fixed-wing, rotorcraft, and vertical-take-off and landing (VTOL) vehicles. Fixed-wing UAVs can efficiently cover large distances, whereas the multirotor design is capable of providing agile movement as well as good stability, allowing for complex 3D mapping. Several studies used gimbals to improve the stability and measurement accuracy of aerial platforms. To maximize the payload capacity of the UAV, sensors along with cameras with built-in gimbal were considered. Cost of commercial UAV can range anywhere from less than \$50 and more than \$50,000 based on the desired level of complexity, specialization, and integrity of the system.

Figure 10. Image of drone being deployed for bridge inspection

CHAPTER 4

Summary and Conclusion

Why Non-Destructive Testing

Of 617,000 accounted bridges in the US, about 42% of those bridges are at least 50 years old, and 7.5% of them are considered structurally deficient. Out of all the bridges, around 33% are steel bridges. These bridges are federally mandated to be inspected every 2 years. Non-destructive Methods allow for confirmation and/or detection of defects that develop over time such as surface cracks, embedded cracks, weld defects like lack of fusion, porosity, etc. The use of these NDE methods incurs cost but if used effectively, they will be the cause of considerable financial savings.

Early Detection and Prevention

Allowing for early detection, NDT methods have proven to save time and money. With the right application and use, these methods are cost-effective and prevent the integrity of structures to be jeopardized. NDT methods allow bridge inspectors and engineers to quickly act after a flaw is assessed and characterized as a defect.

Funding and Research of New Technologies

The funding and research of new and improved methods will help make the inspection of in-service steel bridges safer and simpler. Methods such as UAVs show promising results in improving safety, traffic prevention, and greater data collection. Promoting safety is the most important when working anywhere and investing in these technologies is a must. Not only are you keeping the integrity of the bridge safe but most importantly both workers and civilians.

References

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[redacted]

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Prepared by:

K. Hires, B. Hastings, ATLSS Engineering Research Center, Lehigh University

PennState College of Engineering

LARSON TRANSPORTATION INSTITUTE

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117 ATLSS Dr.
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Shamim Pakzad, PhD. snp208@lehigh.edu, (610) 758-3566

16. Abstract

Characteristic frequencies are the value at which a structure tends to vibrate when exposed to external forces. Each characteristic frequency, also known as a fundamental frequency of vibration, also has a unique associated mode shape. Since these frequencies are fundamental properties of structures, observing trends in these frequencies can build an understanding of the effects of external forces of the health of structures. This report is a comprehensive modal analysis of Gene Hartzell Memorial Bridge. Data is observed from Summer 2021, Fall 2021, and Summer 2022 to document both daily trends and seasonal trends in fundamental frequencies and mode shapes of the bridge. Daily trend observations show a proportional relationship between temperature and frequency, with small changes throughout the day as temperature changes. Seasonal trends show an overall increase in frequency during the summer months and an overall decrease in the fall months, once again illustrating the proportional relationship between temperature and characteristic frequency. Mode shapes observed largely remained consistent throughout the course of a day, but some modes show a seasonal decrease in amplitude with an increase in temperature. Moving forward, this comprehensive analysis can be used to continually assess the health of the bridge. Significant deviations from these trends are a likely indication of poor structural health and further analysis and investigation can be done to assess any possible structural issues.

17. Key Words

Modal Analysis
Characteristic Frequencies, Natural Frequencies
Mode Shapes

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CHAPTER 1

Introduction

BACKGROUND

Current methods of inspection often consist of visual inspections every few years by a team of individuals who are educated on necessary safety standards. However, there are many problems with this method of inspection. For one, it is far too infrequent to ensure the health of a bridge. In the moths or even years between inspections, problems could arise that would go unnoticed and unsolved until the next inspection. Additionally, there is a large opportunity for human error to arise during this process because very few data are taken during these inspections. Small damages to the bridge can go unseen and several parts of the bridge are completely inaccessible for people to access for observation. So, other methods of continuous, data-driven monitoring must be explored to assess the health of these structures more accurately. One method that can be use is the deploying of sensors to monitor a structure’s characteristic frequencies.

Characteristic frequencies are the value at which a structure tends to vibrate when exposed to external forces. These frequencies, along with their unique corresponding damping ratio and mode shape, are fundamental characteristic of all structures. Modal analysis is the study of these frequencies, analyzing properties of structural systems in the frequency domain. Through modal analysis, these fundamental properties of a bridge can be observed over time to monitor changes and effects of external forces such as traffic patterns, weather, and temperature changes. Since these frequencies are fundamental properties of a structure, a significant change in frequency is often an indication that there has been a significant change in the structure (cracking, bending, etc.). Although characteristic frequencies cannot directly indicate what is wrong with a structure, they can indicate general structural health through monitoring trends in both characteristic frequencies and their unique associated mode shapes. If changes are observed to these fundamental properties, further investigation can be taken to resolve any structural issues.

OBJECTIVES

This report is a modal analysis of Gene Hartzell Memorial Bridge. Long-term trends in the characteristic frequency and mode shapes are observed in June-July 2021, September-October 2021, and June-July 2022 to analyze both daily and seasonal trends. By looking at multiple time periods throughout the day as well as multiple seasons, the effects of temperature, weather patterns, and other external forces on these characteristic frequencies can be observed. If health of the bridge is stable, some slight changes are expected along with a change in temperature, but no significant changes (seasonal or daily) should be observed in the characteristic frequencies or mode shapes. With a thorough understanding of these fundamental properties of the structure, the health of the bridge can be more effectively monitored if, and when changes to these patterns are observed.

Figure 1: Gene Hartzell Memorial Bridge, Easton, PA
Source: American Institute of Steel Construction

DATA AND DATA STRUCTURES

Data for this project is collected using a series of strain gauges and accelerometers placed in the first two spans of the bridge (see figure 2). Ten accelerometers and ten strain gauges are deployed across the bridge for a total of twenty sensors equipped to measure the external forces on the bridge (most notably, passing vehicles).

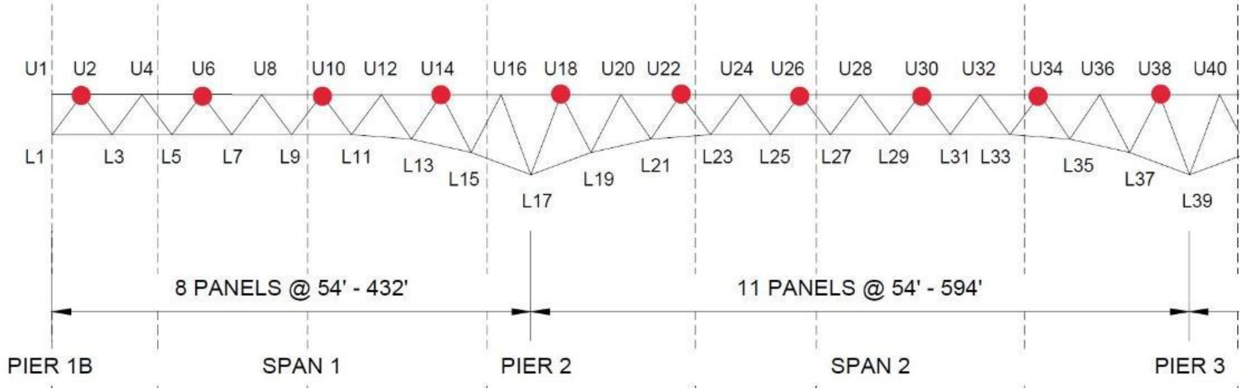

Figure 2. Elevation view with sensor locations. Strain gauges are located at the red dots

Strain gauges have been the most common method of collecting strain data in recent years. However, strain gauges are laborious to install and can be costly - in labor costs and equipment. So, new methods of indirectly measuring strain have been deployed, including using acceleration measurements which Is why accelerometers are also installed on the bridge. The cost of installation of accelerometers is much lower and the data provided is much more robust in quality. Ambient vibrations are collected by the accelerometers on the bridge, and using deep learning architecture, this data is used to predict strain responses (Gulec et al).

Data is collected across a 6–12-hour period, often starting around 10 am in the morning and/or 5 pm in the afternoon. The data collection system is powered by a Honda EU2200i generator, which can run about 12 hours with a full tank of gas under optimal conditions, limiting the data collection time. The sensors take hundreds of samples per second, leading to data files with millions of data points across the 6–12-hour time interval, providing a large data set to accurately perform modal analysis on the structure.

CHAPTER 2

Methodology

INTRODUCTION

Data collected through strain gauges and accelerometers across the spans of the bridge produce busy signals that cannot produce meaningful results without heavy filtration. Noise must be filtered out as well as unwanted frequency signals that are outside of the range of interest. Additionally, all the data collected is given in the time domain. To perform proper modal analysis, data must be moved to the frequency domain to accurately determine natural frequencies of vibration and mode shapes. This requires that the data be fed through several additional algorithms, all detailed below

DATA FILTRATION

Filters must be applied to the data before it can be interpreted. In the case of this study, we are largely interested in the effects of passing vehicles on the bridge. However, there are a lot of external forces acting on the bridge and around the sensors that can busy the signal, creating large amounts of noise that makes it impossible to analyze raw data. Using MATLAB, filters are applied to remove this noise from the busy signal, leaving a data signal that can be more easily fed through necessary algorithms (see section below) for analysis.

Since there is a lot of activity on the bridge, there are often high frequency signals present that are not of interest. So, a second set of filters called bandpass filters are used to cut off very high and very low frequencies that are not of interest. In this case, most frequencies of interest were between .8 Hz and 4.2 Hz.

For the purposes of this experiment, filtration is used to yeild “cleaner” data to use in following algorithms and make analysis more mangeable. However, this filtration can have several effects on the data. One effect that can be observed from this filtration process is the ability to identify peaks in traffic signal patterns. In unfiltered strain data, the vehicle traces can be seen as a vehicle passes along the bridge (see figure 3). The high pass filter that cuts off higher frequencies from the data eliminates the visible effect of vehicle traces from the strain signal. In figure 3 below, an illustration of this can be seen with when a cutoff of 1 Hz is applied to the data. The lower high pass cutoff, however, maintains the vehicle pass effect in the strain data while detrending the data.

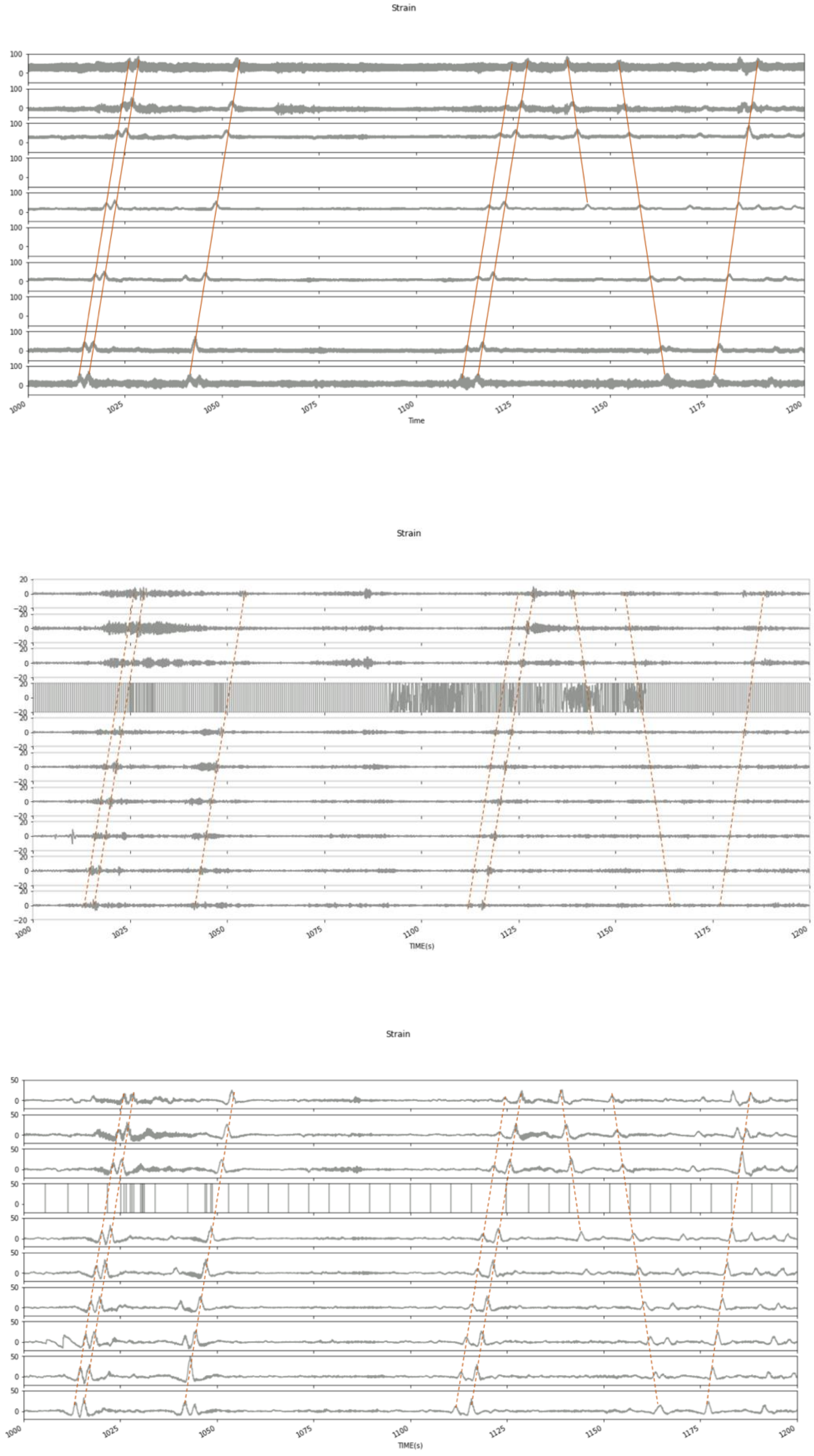

Figure 3: Vehicle Traces in strain data unfiltered (top), with high pass cutoff at 1 Hz (middle) and with high pass cutoff at .1 Hz (bottom)

ALGORITHMS

After filtration, the natural excitation technique – eigensystem realization algorithm (NExT-ERA) is applied to the data. The first step in this process, NExT, takes the ambient signal from the collected data and generates impulse-response signals that can be used in the subsequent modal analysis. An ERA is then used to identify the natural frequencies, mode shapes, and damping ratios of the structure. A single-sided fast Fourier transform is applied throughout the course of this process. This process moves from the time domain to the frequency domain so that the natural frequencies of the bridge can be observed. A single-sided Fourier transform is used in this case because negative frequencies are eliminated in this special type of transform which are not of interest in this case.

Power Spectral Density (PSD) diagrams are then generated for both strain gauge and accelerometer data to provide a visualization of the bridge's characteristic frequencies. In these diagrams, peaks in the graph are observed to determine characteristic frequencies. If a peak appears in several of the strain gauge and/or accelerometer sensors it is noted as an observed natural frequency of the bridge.

In python, the filtered data is used in a different visualization software to note the characteristic frequencies and mode shapes over time. The data is split up into hour-long segments, and characteristic frequencies, mode shapes, and damping ratios are identified for each hour of the data sets. This data is then compiled into a large data set and graphed over days (see figures 3,4,6) or months (see figure 5) to observe trends in these properties over time

CHAPTER 3

Findings

DAILY TRENDS IN CHARACTERISTIC FREQUENCIES

The first trend observed in characteristic frequencies were changes throughout the course of the day. Results showed that as the temperature changes, the characteristic frequency rises and falls proportionally with the temperature. A peak in frequency is often seen around 5 or 6 pm, the same time as peak temperature hours (see figure 4, 5). This trend can be seen in all time periods observed season (summer 2021, fall 2021 and summer 2022), indicating that the natural frequencies of the bridge are regularly impacted by changes in temperature.

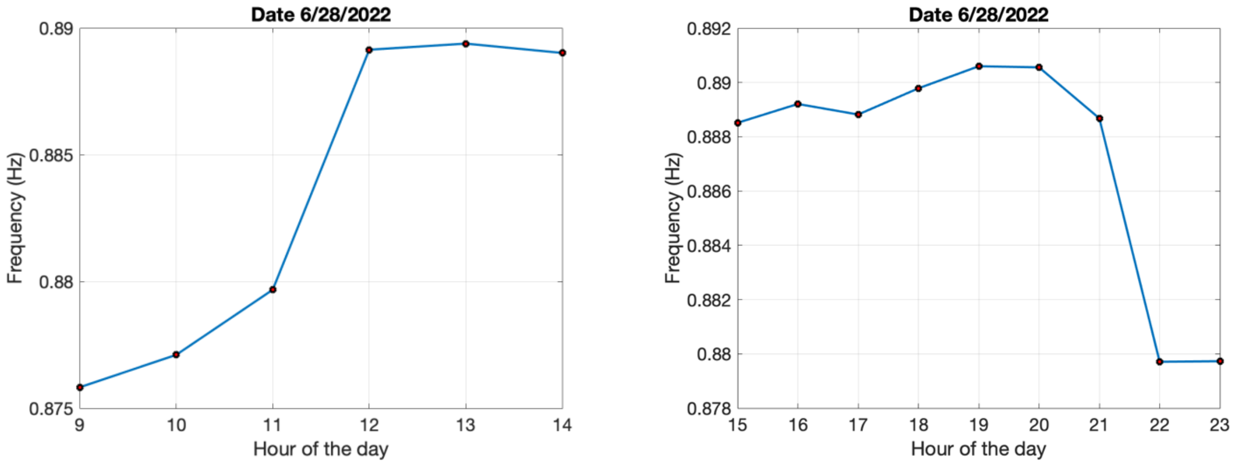

Figure 4: Mode 1 frequency (~0.8) throughout the day on 6/28/2022

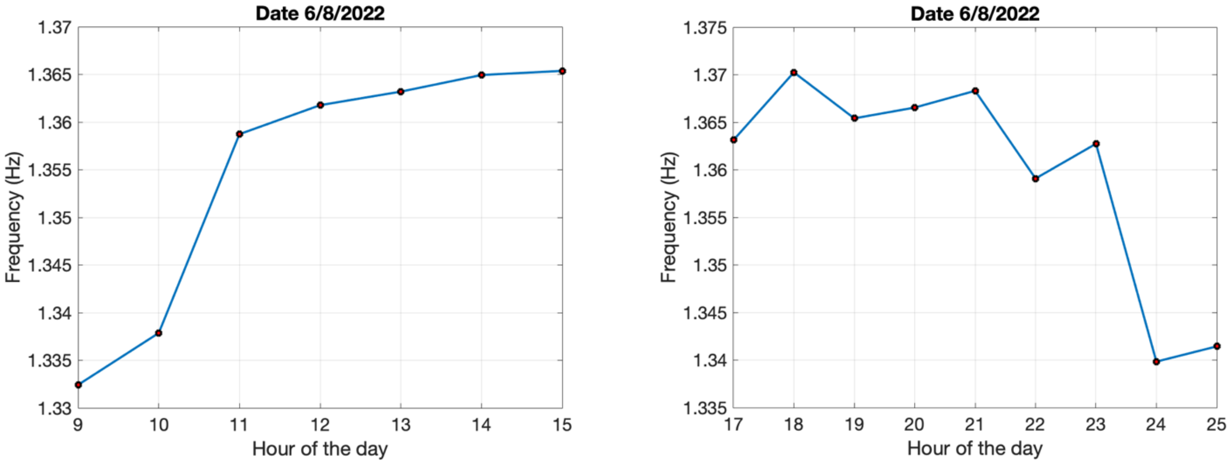

Figure 5: Mode 2 frequency (~1.3) throughout the day on 6/8/2022

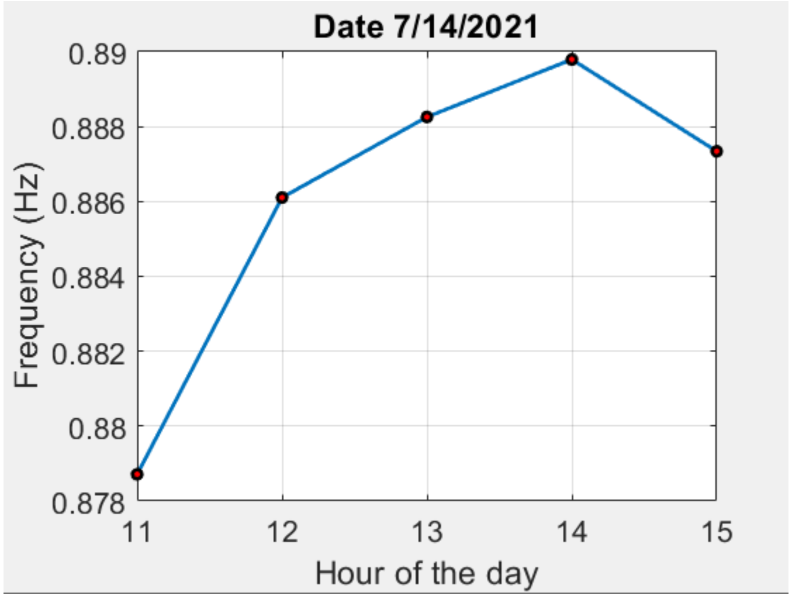

Figure 6: Mode 3 frequency (~1.7) throughout the day on 7/14/2021

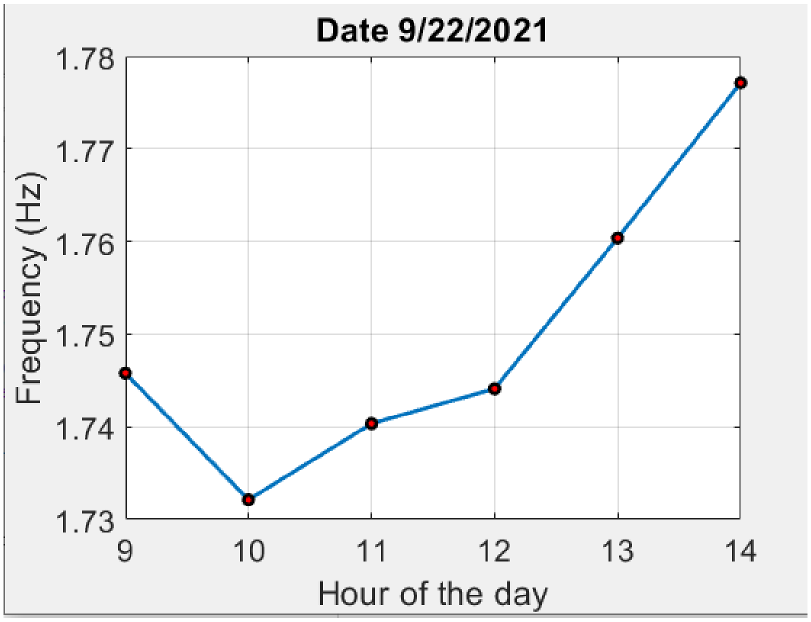

Figure 7: Mode 3 frequency (~1.7) throughout the day on 9/22/2021

SEASONAL TRENDS IN CHARACTERISTIC FREQUENCIES

In modes 1, 2, 3 and 8, there is an increase in frequency during the summer months (June and July) and a drop in the frequency the autumn months (September and October). This trend is similar to the daily trends in that as temperatures increase, the natural frequencies tend to increase as well. Additionally, as seen in figure 8, the summer months have a much more sporadic trend in frequency, likely due to a larger variation in temperatures in the summer months. With this correlation, seen both seasonally and daily, between temperature and characteristic frequency, a certain reasonable range of variance of the frequency can be expected without causing concerns of potential damage on the bridge.

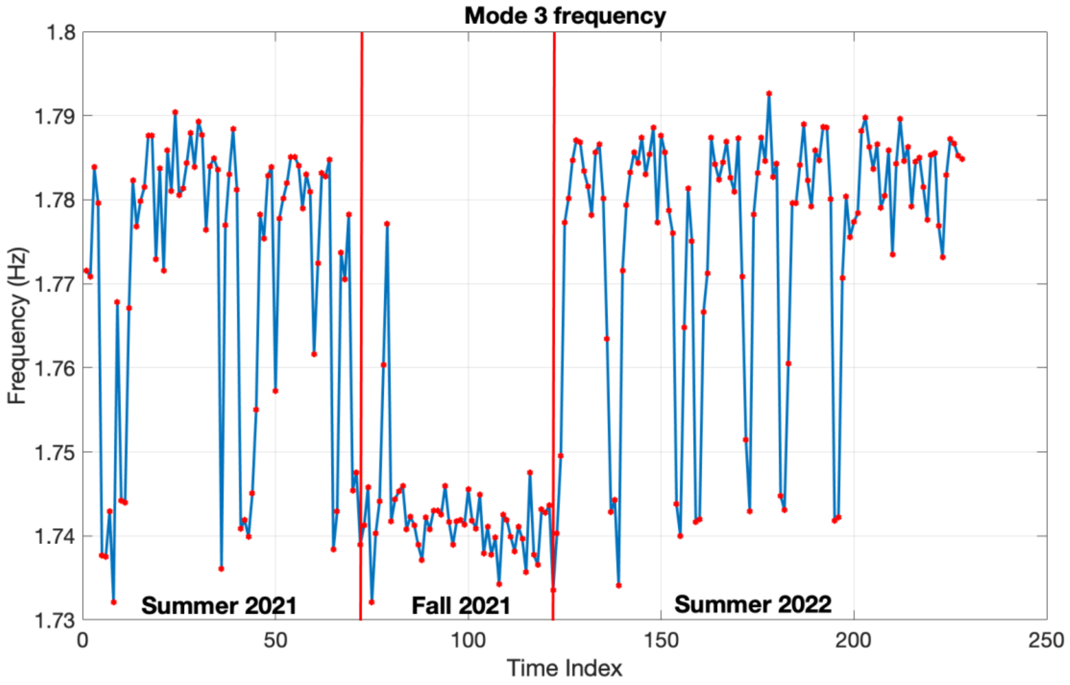

Figure 8: Mode 3 (~ 1.7) in summer 2021 (left), fall 2021 (middle) and summer 2022 (right)

TRENDS IN MODE SHAPE

Certain frequencies have consistent mode shapes that allow for observation of vibration at the structure's natural frequencies. Mode shapes observed largely remained consistent throughout the course of this study. Although the mode shapes tend to stay relatively consistent, some mode shapes show a seasonal decrease in amplitude with an increase in temperature, most notably in modes 4, 5, and 6 (see figure 9). Even with slightly different amplitudes, the general shape of each mode remains the same from day-to-day, which allows a clear cause for suspicion of damage given a consistent drastic change in shape from shapes shown from previous data.

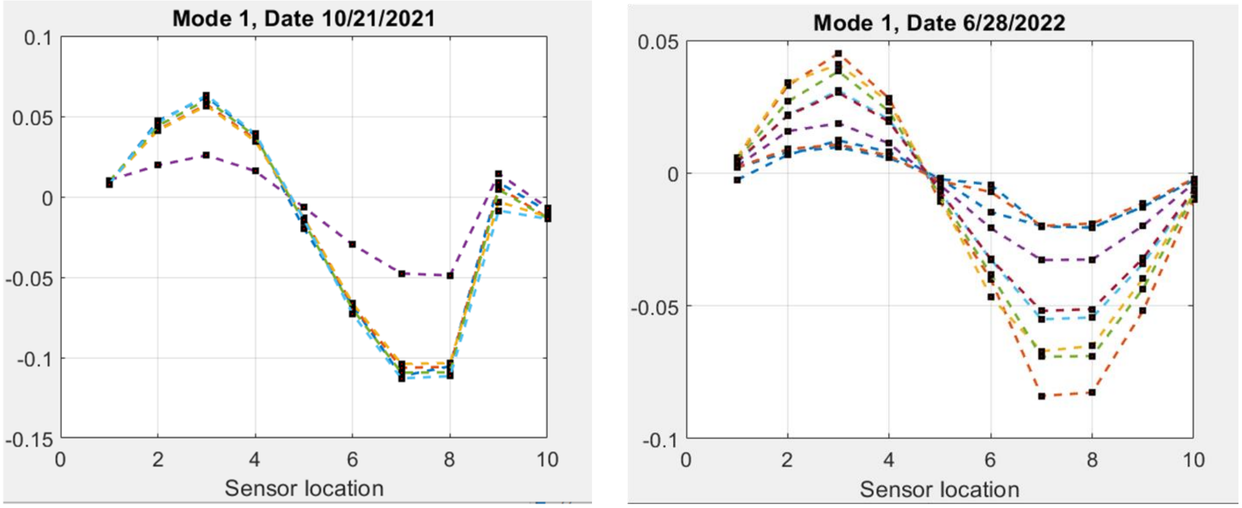

Figure 9: Mode 1 in fall 2021 (left) and summer 2022 (right)

DAMPING RATIOS

Damping ratios were observed and noted as a part of the initial data analysis portion of this project. There was no clear trend (daily or seasonal) observed in the damping ratios, so analysis of the damping ratios is not included in this report. This uncertainty in the data is likely a product of the models used to obtain damping ratios, which are extremely simplified and cannot adequately reflect the damping properties of this large and complex structure.

CHAPTER 4

Recommendations

FUTURE RESEARCH

Research conducted in this study should continue to gain a more comprehensive understanding of trends in characteristic frequencies. With constant monitoring, it will be easier to determine at what point the changes in the characteristic frequencies become cause for concern. With the understood correlational relationship between temperature and frequency, slight variance can and should be expected throughout both the course of the day and across the seasons. However, further research should be done to set a range of expected variation. This would allow for an efficient and more clear, sure way to know when a change in frequency is due to damage to the structure, as opposed to simply a response to external variables (traffic, weather, ect.). In addition, more continuous studying of the bridge should be done to monitor any changes in the data that could alert to damage in the structure.

Sensors have been installed on the pier caps of Gene Hartzell Memorial Bridge and data collection is expected to begin shortly. Through monitoring the effects of external forces and performing modal analysis on another portion of the bridge that has less reinforcements than the main spans of the bridge, a more comprehensive understanding can be built of the trends in characteristic frequencies. Furthermore, continuous smart data collection is beginning to be implemented as a different technique for acquiring necessary data, including the use of mobile devices and transitioning to a more accelerometer focused approach.

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