Quarterly Progress Report

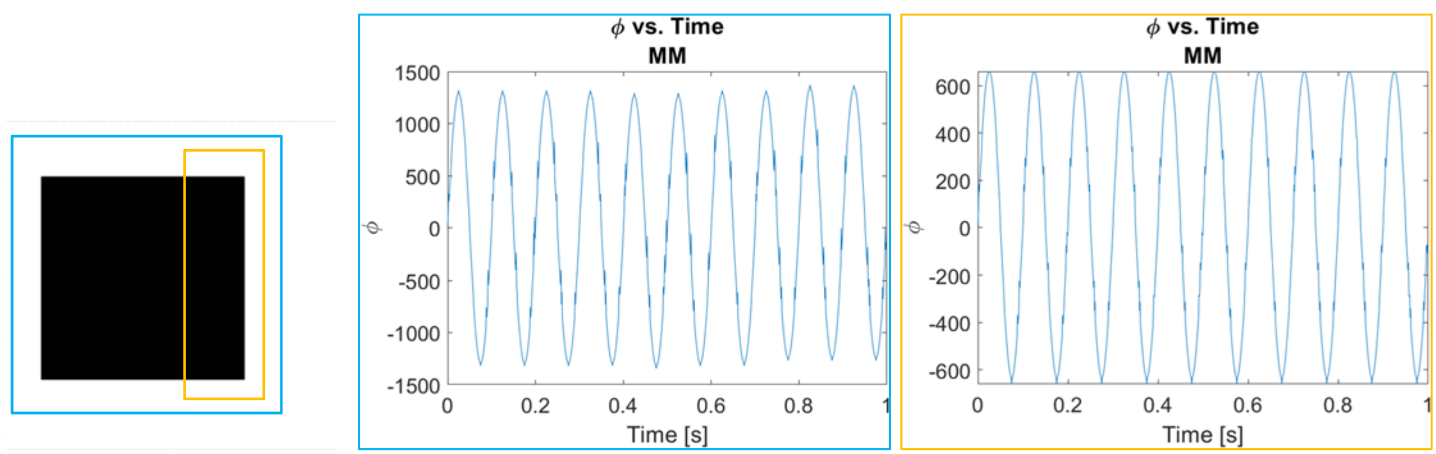
Project Number and Title: 3.8 Bridge Modal Identification via Video Processing and Quantification of Uncertainties
Research Area: Thrust 3 – New Systems for Longevity and Constructability
PI: *Zhu Mao, University of Massachusetts Lowell*
Co-PI(s): *Co-PIs and home institution(s)*
Reporting Period: *04/01/2021-06/30/2021*
Date: *06/30/2021*

Overview: **(Please answer each question individually)**

This project has as objective investigate the capability of applying non-contact optical sensing and motion magnification to identify structural dynamics and damage in a truss bridge. Previously, experiments on the equipment were performed in the Olney Hall Bridge, on the campus of UMass Lowell, and then an in-situ test of the new Grist Mill Bridge, located at Hampden, Maine was conducted as part of Project C11. During this reporting period, the test was performed and the data collected were processed in order to obtain dynamic information of the bridge. In addition, a $10,000 cash donation from NEC Labs was received in this reporting period, and a collaborative investigation of the transportation infrastructure durability and testing is initiated.

Currently, the technique used to extract dynamic information from video-based sensing in this project is the Phase-based Motion Estimation (PME), which allows to extract information from a moving object or from a region of interest of a vibrating structure based on a convolution between the sequence of frames and the Gabor Wavelet. Although the phase extracted contains the position information of the region of interest, being effective to extract the natural frequencies and mode shapes of the structure and subpixels movements. Usually, its position is extracted qualitatively as "phase", which unless having another sensing technique it is not possible to obtain its correct amplitude in displacement units. There are other techniques that can extract the movement quantitatively such as KBOS, which uses markers with sine waves pattern in order to obtain quantitative results [1]. Other techniques which can extract quantitative results often rely on markers or speckle patterns that must be placed at the structure.

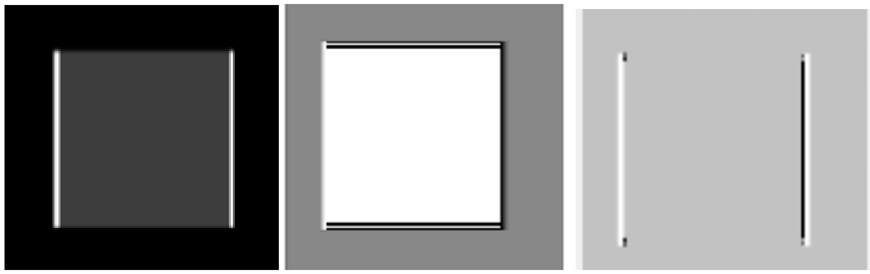
In order to better understand PME and to quantify its output, a synthetic video of a moving block is created shown in Figure 1a). Its motion was estimated using PME at different regions of interest, on Figure 1b) using the whole block as the region of interest, the response will have an amplitude of around 1300 while for the blue box on Figure 1c) the amplitude will be around 650 while for both cases the block is moving only 2 pixels. PME convolutes the frames with the real and imaginary parts of the Gabor wavelets, generating a complex number, which can be converted into a magnitude and phase.



(a) (b) (c)

Figure 1. (a) Block moving 2 pixels in a sinusoid motion, (b) time response using the red box as region of interest, (c) time response using the blue box as region of interest.

Figure 2 shows its features for the same block presented in Figure 1a).



(a) (b) (c)

Figure 2. (a) video frame, (b) phase of the block presented in Figure 1a) and (c) the gradient of the phase on horizontal.

The change in the phase from frame to frame will then be summed for each pixel and the final result are plotted in Figure 1b) and 1c). As the change of the phase will be summed to extract the movement, and regions with the same amplitude will have a zero difference between frames, extracting the gradient of the phase will show the region that will be added during the change of frames as it can be seen in Figure 2c). Using a weighted average of the pixels intensities as in the Eq. (1) will achieve a mean displacement.

$$A_{moving} = \sum_{i=1}^{N}\sum_{j=1}^{M}\frac{|f(i,j)|}{\max(f(i,j))} \tag{1}$$

The final result can be seen in Figure 3. Even though the regions of interest are different, the final displacement will have 2 pixels amplitude for both of them.

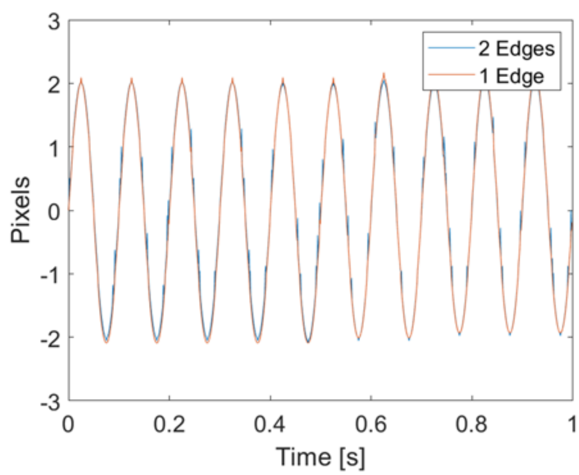


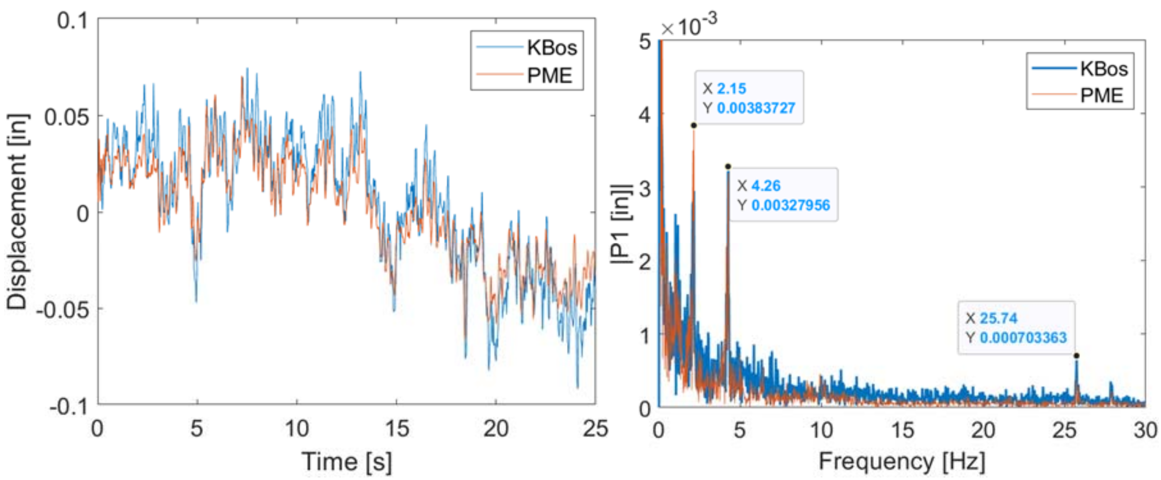
Figure 3. Displacement in pixels for both regions of interest showed in Figure 1a).

After achieving good results on an artificially generated video, the algorithm was applied into the data collected at the Olney Hall Bridge at UMass Lowell. Figure 4a) shows the bridge of the test, which was used different optical techniques to extract information. Initially, results from KBOS and PME were compared, on Figure 4b, it is possible to see the region of interest for both algorithms. Later, the results were compared to a Laser Doppler Vibrometer (LDV), with the region of interest shown later on Figure 6a).

(a) (b)

Figure 4. (a) Olney Hall bridge, UMass Lowell, (b) regions of interest for KOBS (orange) and PME (blue).

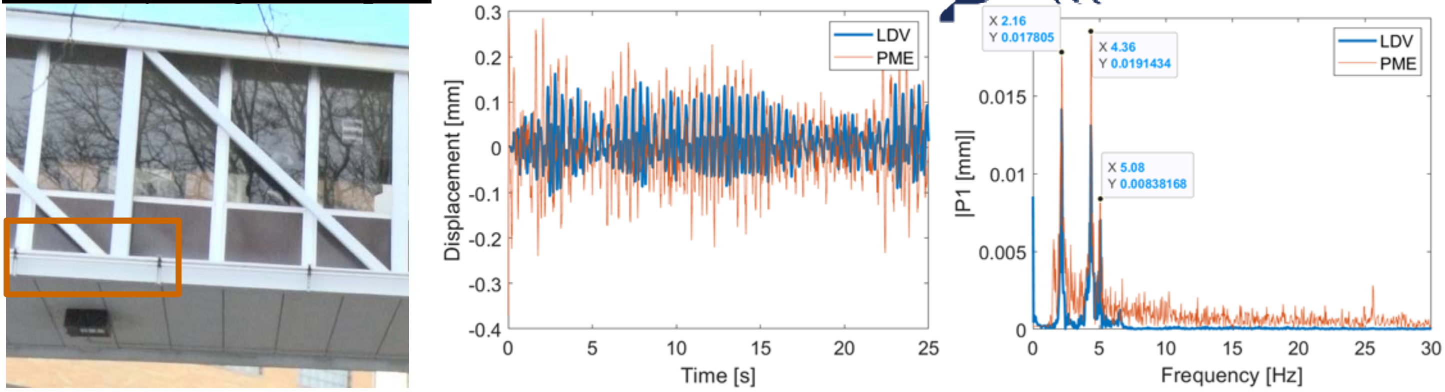
As it can be seen in Figure 5 both methods had a very similar amplitude for both the time and frequency response amplitudes. It also had the same behavior, keeping the same natural frequencies when observing for both methods, showing that the PME algorithm had a good accuracy without targets or surface preparation.



(a) (b)

Figure 5. (a) Time and (b) frequency response comparison between KBOS and PME.

As the LDV extracted information in another region of the structure, the PME algorithm was executed again at the new region. This new region of interest can be seen in Figure 6a). Its time and frequency response comparison can be seen in Figure 6b) and 6c). It is possible to observe that for the frequency response, although the amplitudes were not the same, the natural frequencies perfectly matched. In addition, it is possible to verify from the time response that the amplitudes did not match, however, they had the same order of magnitude being both on the decimals of millimeters of displacement. Since the data was collected by two distinct sensors, they were not synchronized, which can lead to error if the sections of data chosen are different. In addition, there is a possibility for error on the assumption of the pixel resolution. As the data was not synchronized, in addition to the time response the root mean square (RMS) of both signals were calculated in order to analyze its error. The RMS value obtained by the LDV was 0.05mm while for the PME was 0.08mm, confirming that although it has a high percent error, the technique does not require any targets and can extract the right order of magnitude on the vibration of structures.



(a) (b) (c)

Figure 6. (a) Region of interest for LDV and PME. (b) Time and (c) frequency response comparison between LDV and PME.

This improvement on phase-based motion estimation, showed great potential for video-based quantification of vibration, since it can extract subpixel movements and does not require targets or any surface preparation, requiring only the distance between the camera and the bridge to achieve the pixel resolution. In addition, data acquisition from camera-based sensing techniques can obtain full-field dynamic information and with less testing time if compared to LDV. For the next reporting period, studies on how to improve the accuracy of the technique will be done, in addition to tests in other bridges to confirm its applicability.

Table 1: Task Progress			
Task Number	**Start Date**	**End Date**	**% Complete**
Task 1: video motion magnification	9/1/2019	5/30/2021	85%
Task 2: non-contact modal analysis	9/1/2019	9/1/2020	100%
Task 3: machine learning	9/1/2019	8/31/2021	70%
Task 4: nonlinear modal analysis	1/1/2020	12/31/2021	20%
Overall Project:	9/1/2019	12/31/2021	

Table 2: Budget Progress		
Project Budget	**Spend – Project to Date**	**% Project to Date***
$55219.5	$ 48434.8	87.7% as of 6/30/2021

Include the date the budget is current to.

Table 3: Presentations at Conferences, Workshops, Seminars, and Other Events				
Title	**Event**	**Type**	**Location**	**Date(s)**
Bridge Modal Identification via Video Processing and Quantification of Uncertainties	TIDC 1st Annual Conference	Conference meeting	UMaine	June 6-7, 2019
Bridge Modal Identification via Video Processing Motion Magnification	Northeastern Society for Experimental Mechanics Conference	Conference	UMass Dartmouth	June 22nd, 2020
Bridge Modal Identification via Video Processing and	TIDC 2nd Annual Conference	Conference meeting	UML	August 12, 2020

Quantification of Uncertainties				
Optical-Based Structural Health Monitoring of Truss Bridges	2020 TIDC Annual Student Poster Contest	Competition	Online	October 21,2020
Infrastructure State Awareness and Dynamics Identification via Advanced Sensing	NEC Laboratories America, Inc.	Seminar	Online	January 4, 2021
An Optical Mode Shape-Based Damage Detection Using Convolutional Neural Networks	International Modal Analysis Conference	Conference	Online	February 11, 2021

Table 4: Publications and Submitted Papers and Reports				
Type	**Title**	**Citation**	**Date**	**Status**
Conference Proceedings	Motion magnification for optical-based structural health monitoring	https://www.spie.org/SS20/conferencedetails/health-monitoring-structural-biological-systems	04/27/2020-04/30/2020	Full paper published
Conference Paper	An Optical Mode Shape-Based Damage Detection using Convolutional Neural Networks		0/11/2021	Full paper in press

Participants and Collaborators:

Table 5: Active Principal Investigators, faculty, administrators, and Management Team Members			
Individual Name	**Email Address**	**Department**	**Role in Research**
Zhu Mao	Zhu_Mao@uml.edu	Mechanical Engineering	PI
Tzuyang Yu	Tzuyang_Yu@uml.edu	Civil Engineering	Collaborating on bridge testing and sensor placement; providing lab-scale testbed for algorithm validation
Xingwei Wang	Xingwei_Wang@uml.edu	Electrical Engineering	Collaborating on bridge testing and sensor placement; providing lab-scale testbed for algorithm validation

Table 6: Student Participants during the reporting period				
Student Name	**Email Address**	**Class**	**Major**	**Role in research**
	Email is not included in the external report and is only used for internal purposes.	(i.e. Junior, Master's Ph.D)		
Celso do Cabo		Ph.D.	Mechanical Engineering	Key personnel to conduct the

				theoretical investigation
Nicholas Valente		Ph.D.	Mechanical Engineering	Idea discussion, and helping on tests and data processing
Mark Todisco		M.S.	Mechanical Engineering	Idea discussion, and helping on tests and data processing

Table 7: Student Graduates			
Student Name	**Role in Research**	**Degree**	**Graduation Date**
Aral Sarrafi	Key personnel to conduct the theoretical investigation	Ph.D.	Spring 2019
Matthew Southwick	Idea discussion, and helping on tests	M.S.	December 2020

Table 8: Research Project Collaborators during the reporting period						
Organization	**Location**	**Contribution to the Project**				
		Financial Support	**In-Kind Support**	**Facilities**	**Collaborative Research**	**Personnel Exchanges**
NEC Laboratories America, Inc.	Princeton, NJ	x		x	x	

Table 9: Other Collaborators			
Collaborator Name and Title	**Contact Information**	**Organization and Department**	**Contribution to Research**
N/A			(i.e. Technical Champion)

Changes:

In addition to the planned modal identification approaches that will be applied, machine learning and nonlinear modal analysis will be adopted too. Review of literatures has been deployed in the past reporting period, and these new techniques will be a successful complement to the bridge assessment. No cost extension has been requested due to the impact from COVID.
As abovementioned, an industry collaboration is initiated and we will fine-tune the research emphasis with our better understanding of the industry needs.

Planned Activities:

In the next reporting period, we will focus on the following challenges.

- Identify and isolate the mode shapes of the Grist Mill bridge based on the data collected
- Study the possible methods of nonlinear modal analysis and choose the best approach to the truss-bridge structure
- Compare non-contact sensing with traditional sensing modalities in a metallic structure
- The lab-scale truss bridge will be kept utilized for testing new models of data extraction to provide realistic data.
- Non-contact sensing will be adopted and more in-depth investigation of selecting pixels, especially a big number of pixels to take advantage of the averages. By doing this, a better estimation of the modal information will be

expected, but this is contingent on the data quality at the selected pixels. Trimming and cropping the videos prior to calculating the expected resonance frequencies may also help enhance the performance.

- Applying other sensing modalities, and maybe collaborating with other projects, in identifying frequencies using conventional data acquisition method. This will help design a better band-pass filter in getting mode shapes and motion magnification results. This effort will be cohered with other UMass Lowell faculty.
- Machine learning algorithms will be studied in the next reporting period to provide an improvement of the results of this period and an option in classifying different damaged types and possibilities for damage localization.
- Collaborate with NEC Labs America.
- Comparison of Grist Mill Bridge results obtained from multiple sensing modalities
- Improvement of current model, by changing the type of materials, elements and excitation to obtain a more realistic model