Title: Bridge Health Monitoring Using Linear and Nonlinear Approaches: Experimental Validation

Authors:
Kevin Cross
Ratneshwar Jha
Matthew Whelan
Kerop Janoyan
Michael Gangone

ABSTRACT

This paper focuses on the application of two methodologies, namely modal curvature and instantaneous phase, for bridge health monitoring. The algorithms are applied to the structural vibration data acquired from experimental bridge model, which includes common damage scenarios. The modal curvature method utilizes the second derivative of structural mode shapes acquired using the peak picking method. Instantaneous phase information is derived through the Hilbert transform of intrinsic mode functions generated from the decomposition of vibration data. The curvature method demonstrates ability to detect damage, but needs further development to predict damage location. The instantaneous phase method fails to detect damages for ambient vibrations.

INTRODUCTION

The goal of structural health monitoring (SHM) is to develop a damage detection algorithm that can determine and classify damage (location, type, and severity), while eliminating false indications for a dynamic system exposed to varying environmental and operational load conditions as well as instrumentation noise (i.e., ‘real world’ conditions). An extensive review of SHM methods was presented by Doebling et al. [1] and Sohn et al. [2]. The proceedings of the structural health monitoring conferences held at Stanford University every two years, edited by Chang [3], contain thousands of papers dealing with advancements in SHM. A literature review reveals that numerous approaches for extracting damage sensitive features based on ambient vibration measurements have been investigated. Although this field has experienced significantly increased research during the last decade, a damage detection method that can provide quantitative damage information anywhere in a complex structure, such as a bridge, is still under development.

Structural vibration based health monitoring methods allow for numerous, relatively small, sensors to be deployed throughout the structure. Wireless vibration sensors significantly reduce cost and provide for easy data transfer. Historically vibration data are analyzed to determine natural frequencies and mode shapes of the

Clarkson University, 8 Clarkson Ave, Potsdam, New York, 13699-5725, USA

structure. Salawu [4] found that damage detection using natural frequencies is not very reliable. Pandey *et al.* [5] utilized the curvature of the structural mode shapes for damage detection. The curvature method uses Fourier analysis and assumes that large structures have linear elastic behavior and that any incurred damage causes a noticeable loss in its elasticity. Unger *et al.* [6] studied, both numerically and experimentally, damage in a prestressed concrete beam using mode curvature obtained from measured strains. Farrar and Jauregui [7] successfully implemented the modal curvature method for damage identification on a full size bridge. Our previous work with modal curvature has shown the ability to detect damage and location on a numerical benchmark bridge [8].

The Hilbert-Huang Transform (HHT), proposed by Huang *et al.* [9], represents another approach for analysis of data, including nonlinear and non-stationary signals. This method decomposes any time series data into a finite and often small number of 'intrinsic mode functions' (IMF). The Hilbert transform of IMFs produces instantaneous phase (and frequency) as a function of time. This paper focuses on the application of modal curvature and instantaneous phase methods for damage detection of an experimental bridge model built at Clarkson University for SHM purposes.

METHODOLOGY

Modal Curvature Method

Fourier transform is the classical method of analyzing structural vibration signals to extract natural frequencies and mode shapes. The modal curvature method uses the second derivative of a mode shape denoted by $v''(x)$. Equation 1 gives the well-known beam equation where *M(x)* is the bending moment and *EI* is the flexural stiffness.

$$v''(x) = \frac{M(x)}{EI} \tag{1}$$

The basic principle of the modal curvature method states that damage to a structure results in a net loss of stiffness [10]. Ideally the area within the mode shape with the greatest change in curvature corresponds to the location of the incurred damage. We use the PSD function in Matlab and the peak picking method to determine the eigenvalues (natural frequencies) of the structure [11]. The magnitudes of the selected peaks are related to its corresponding eigenvectors, or mode shapes. The mode shapes fitted to a surface using the minimum number of grid points possible to include the locations of all the sensors. The surface is created using the *griddata* function in Matlab and the discrete Laplacian (Eq. 2) is used to compute the second derivative (*del2* function in Matlab). Here the second derivative of the surface defined by *u* is taken to produce the Laplacian, *l*.

$$l = \frac{\nabla^2 u}{4} = \frac{1}{4}\left(\frac{d^2u}{dx^2} + \frac{d^2u}{dy^2}\right) \tag{2}$$

A damage index, called the curvature difference (*CD*), is defined by taking the absolute value of the difference in curvature at each grid point for any damage *D*, from those of an established baseline *B*, for each particular mode as given in Eq 3.

$$CD_{ij} = \left| B_{ij} - D_{ij} \right| \tag{3}$$

The CD surface can display damage severity over an area representing the bridge, and thereby helping to identify damage location. By summing *CD* for all accelerometers *Ns*, and for all modes *Nm*, we define the *Total Curvature Difference TCD*, as an overall damage index (Eq 4).

$$TCD = \sum_{m=1}^{Nm} \sum_{n=1}^{Ns} CD_{mn} \tag{4}$$

Instantaneous Phase Method

The Hilbert-Huang Transform [9] produces instantaneous phase, frequency and energy, rather than global values as given by the Fourier transform. The total instantaneous phase is defined by a sum of the instantaneous phases for each IMF. The total phase is unwrapped from its harmonic nature to reveal a linear trend which is used as a damage indicator. Further details of the method are given in Jha, *et al* [10].

EXPERIMENTAL SETUP

The experimental setup consists of a bridge model configured to simulate properties of a full sized bridge structure. The structure consists of a single span (4 meters) utilizing two girders. There are a total of five cross members tying the girders together. The girders and cross members are made from standard S3-5.7 I-beams. These are bolted together through their web via 2in angle iron brackets using several grade 8 1/4in bolts with a torque of 10ftlbs. The deck consists of two layers of steel plate, one 14 gauge and the other 11 gauge, arranged in the four separate sections created by the cross members. The deck is bolted uniformly to the girders and cross members in several locations using grade 5 1/4in bolts with a torque of 5ftlbs. The structure is attached to four large steel columns by an intermediate support bracket created from 6in C-Channel welded to a 1/4in steel plate. The bridge is connected to its supports via four 1/4in grade 8 bolts with 4ftlbs of torque at each connection with a layer of rubber. An overall picture of the bridge with half the deck can be seen in Fig 1.

Figure 1: Laboratory Bridge Model for Diagnostics and Damage Detection

Controllable damages were introduced to the structure to represent four common damage scenarios (settlement of foundation, stiffness change in the support, stiffness change of joints, and reduced member stiffness). Settlement of foundation was simulated by adding a 1/8in plate between the column and support bracket creating an upward shift in one of the corners. The change in stiffness at the support was simulated with three different severities. First the torque was reduced to 2ftlbs at a specified corner, then fully removing the bolts at the same corner, and finally removing the bolts of both corners on the same end. Change in the stiffness of joints was simulated on a cross member with three severities; First loosening the bolts to 5ftlbs for a joint, then removing the bolts on that side, and finally removing the bolts of both sides of the cross member. Reducing member stiffness was simulated by removing plates from the decking system. Plates were removed one at a time for both an end plate and middle plate case.

For this initial experimentation the model was only subjected to low level ambient vibrations. For each damage case 10 data sets were taken, while the healthy structure included 20 data sets, 10 for a baseline and the other 10 for comparison purposes. The locations of the sensors are shown in Fig 2. The accelerometers utilized in all test sequences are LIS2L02AL low-noise dual-axis MEMS accelerometers manufactured by STMicroelectronics. These sensors feature a +/-2g full-scale range with a 2kHz bandwidth that includes static acceleration. The ultra-low 30 $\mu g/\sqrt{Hz}$ noise density allows for resolution of signals below 0.25mg over the signal bandwidth investigated. The sensors are mounted on custom circuit boards and potted in epoxy within a case to maintain the high natural frequency of the sensor element [12]. Data was collected in real-time across the network of 40 channels (20 wireless nodes sampling 2 acceleration axes each) with an effective sampling rate of 128Hz. In this implementation, the data is sampled at 512Hz, passed through a 57-tap equiripple digital low-pass filter, and down-sampled to the 128Hz effective sampling rate. The composite analog and digital filtering results in nearly zero attenuation of the signal within the 0-50Hz passband.

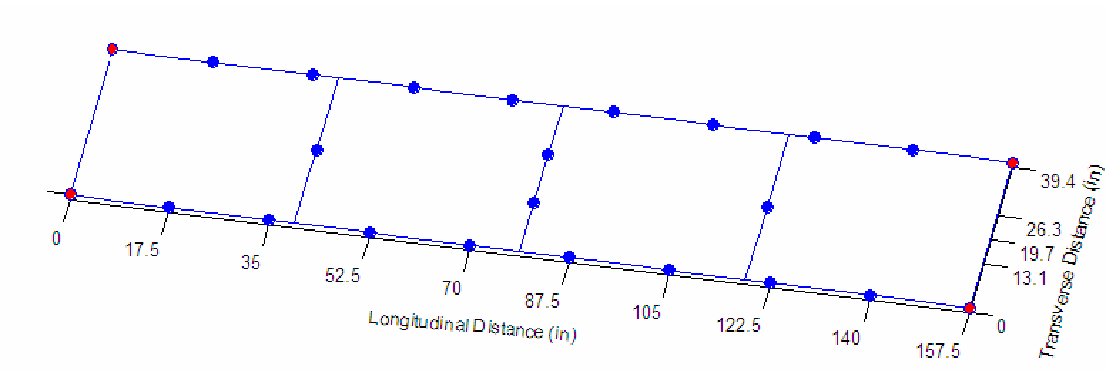

Figure 2: Accelerometer Instrumentation Layout

RESULTS

Modal Curvature Method

We were able to detect the first four natural frequencies in the averaged PSD spectrum created from the different sensors for each run. The natural frequencies selected for each of the damage cases are displayed in Table 1. The frequencies themselves show small shifts in value when compared to the severity of the damage induced on the bridge for the different scenarios. This trait limits natural frequency monitoring as a useful damage index for SHM purposes.

TABLE I. NATURAL FREQUENCIES (Hz)

		Connection			Midplate	
Mode	**Healthy**	**Half**	**Loose-One Side**	**Loose-Both Sides**	**Single Plate**	**Both Plates**
1	11.5	11.5	11.5	11.5	11.875	12.125
2	14.75	14.875	14.875	14.875	15.5	15.25
3	23.75	24.125	24.125	24.125	22.875	23.75
4	41.625	41.625	41.5	41.125	41.625	41.625

	Endplate		Supports			
Mode	**Single Plate**	**Both Plates**	**Half**	**Loose-One Side**	**Loose-Both Sides**	**Displaced**
1	11.625	11.625	11.5	10.75	10.125	11.5
2	14.875	14.75	14.75	14.125	13.5	14.75
3	23.75	18.125	24	23.625	23	24.125
4	41.625	41.625	41.875	41.5	40.125	41.875

The four frequencies, displayed in Table 1, were used to find the corresponding mode shapes via the peak picking method [10]. The mode shapes were then fitted to a grid using the minimum number of grid points necessary to ensure that sensors lined up at a grid point. The surfaces were then used for analysis by the modal curvature method. To create a baseline, we took the average of the first four mode shapes from the healthy data sets. For the various damage cases, the average mode shapes resulting from their 10 data sets were computed and normalized. A second set of healthy runs was also used for comparison purposes.

The discrete Laplacian of the average normalized mode shape was then computed for the healthy and damaged structures creating a curvature surface. However, because there were no sensors located at the supports of the bridge we had to arbitrarily set the points there to zero acceleration. The absolute value of the difference between the healthy and damaged curvature values, *curvature difference CD*, was used as a damage indicator. However, it failed to produce meaningful surface changes to represent location and thus will not be shown in this paper. The lack of location detection might be a result of the arbitrary setting of support points to zero excitation combined with the Laplacian effects on a non uniform sensor grid. The surfaces did however display a change in the magnitude of their peaks representing a change in the stiffness in the structure and indicating the presence of damage.

An overall indication of damage is displayed by using the total curvature difference, TCD. TCD is a summation of all the points on the CD surface that correspond to a sensor location computed according to Eq 4. The results of the TCD calculation are show below in Fig 3. In all the cases we can clearly see a significant change between healthy and damaged cases. The two plate removal cases clearly show damage and increasing severity. In the endplate case with a single plate removed, the TCD value seems low. This may be a result of the arbitrary setting of support points to zero excitation. The Connection and Support cases show an interesting drop in TCD when both sides are damaged compared to a single side. This same behavior was also noted in our previous work with a numerical model [7]. The resulting drop could be a result of reintroduced symmetry in the system by having mirroring damage on both sides of the structure producing smoother curvatures than a single location with damage.

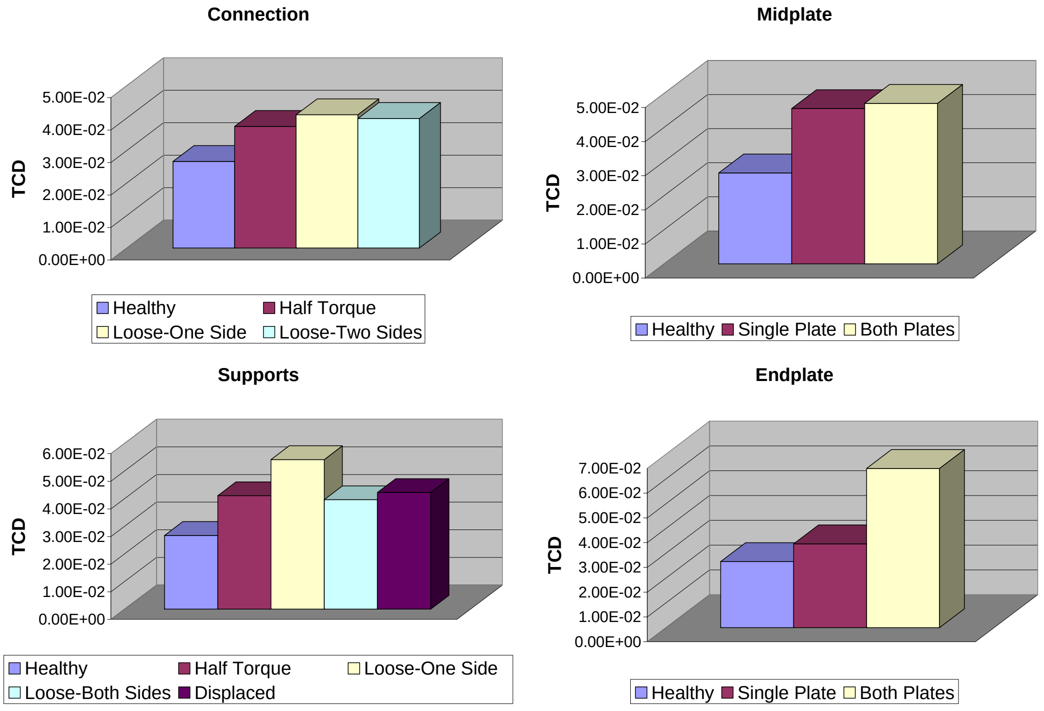

Figure 3: TCD Figures for Different Damage Scenarios

Instantaneous Phase Method

The instantaneous phase algorithm was applied to the data from the experimental setup. The highest value of the unwrapped phase was recorded for each run. An average of the 10 healthy data sets was then computed with its standard deviation for a statistical baseline. To check the robustness of the algorithm, another set of healthy data sets was then produced and its average computed. The averages in comparison stayed well within the confidence interval of the established baseline as shown in Fig 4. The figure indicates that the instantaneous phase method has very little sensitivity to induced damage created with both midplates being removed. The figure shows that this method failed to produce any statistically different responses to damage scenarios. The results for other damage cases are similar and hence not shown here.

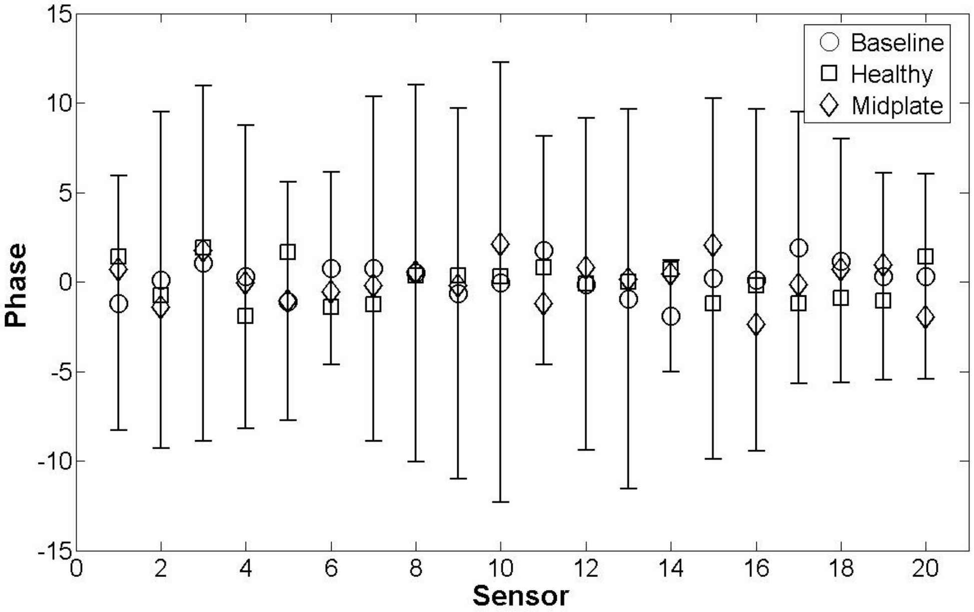

Figure 4. Average Peak Values of Unwrapped Phase

CONCLUSIONS

Modal curvature and instantaneous phase methods were applied to the experimental bridge model. The only excitation to the structure was the ambient vibration received through the floor. Acceleration data was recorded at several sensor points on the structure. The modal curvature method showed promise in its ability to detect damage presence. However, the method needs further refinement to correctly indicate damage location and the effects of damage symmetry on severity. The instantaneous phase method did not produce significant results for damage detection. Future work will focus on improving the modal curvature method and its application to experimental data including sensor grid refinement and the addition various excitation methods.

ACKNOWLEDGEMENTS

This research has been partially funded by a grant from New York State Energy Research and Development Authority (NYSERDA) with additional funding from the New York State Office of Science, Technology, and Academic Research (NYSTAR) Center for Advanced Material Processing (CAMP). Any opinions, findings, and conclusions or recommendations expressed in this paper are those of the authors and do not reflect the views of the funding agencies.

REFERENCES

1. Sohn, H., Farrar, C. R., Hemez, F. M., Shunk, D. D., Stinemates, D. W., and Nadler, B. R. (2003), "A Review of Structural Health Monitoring Literature: 1996–2001," Los Alamos National Laboratory Report, LA-13976-MS.
2. Chang, Fu-Kuo (ed), Structural Health Monitoring 2005: Advancements and Challenges for Implementation, Proceedings of the 5th International Workshop on Structural Health Monitoring, Stanford University, CA, September 12-14, 2005.
3. Salawu, O. (1997), "Detection of structural damage through changes in frequency: a review," Engineering Structures, 19, 718–723.
4. Pandey, A.K., Biswas, M. and Samman, M.M. (1991), "Damage detection from changes in curvature mode Shapes," Journal of Sound and Vibration, 145(2), 321–332.
5. Unger, J. F., Teughels, A., De Roeck, G. (2005), "Damage Detection of a Prestressed Concrete Beam Using Modal Strains," Journal of Structural Engineering, September, pp.1456-1463
6. Farrar, C. R., Jauregui D. A. (1998), "Comparative Study of Damage Identification Algorithms Applied to a Bridge: I. Experiment," Smart Material and Structures Journal, 7, pp. 704-719
7. Cross, K., Jha, R., Whalen, M., Janoyan, K., "Numerical Evaluation of Hilbert-Huang Transform and Fourier Spectrum for Benchmark Bridge Health Monitoring," *Engineering Mechanics Division Conference of the American Society of Civil Engineers*, 3-6 June 2007, Blacksburg, VA.
8. Huang, N. E., Shen, Z., Long, S. R., Wu, M. C., Shih, H. H., Zheng, Q., Yen, N., Tung, C. C., and Liu, H. H. (1998), "The Empirical Mode Decomposition and the Hilbert Spectrum for Nonlinear and Non-Stationary Time Series Analysis," Proceedings of the Royal Society of London A, 454, pp. 903-995.
9. Alvandi, A., Cremona, C. (2006), "Assessment of Vibration-Based Damage Identification Techniques," Journal of Sound and Vibration, 292, pp. 179-202
10. Peters, B. (2000), "System Identification and Damage Detection in Civil Engineering," PhD Dissertation, Katholieke Universiteit Leuven, December 2000.
11. Jha, R., Cross, K., Janoyan, K., Sazonov, E., Fuch*, M., Krishnamurthy*, V., "Experimental Evaluation of Instantaneous Phase Based Index for Structural Health Monitoring," SPIE Paper Number 6173-51, Smart Structures and Materials and NDE for Health Monitoring and Diagnostics, 26 Feb.-2 March 2006, San Diego, CA.
12. Whelan, M.J., Gangone, M.V., Janoyan, K.D., Cross, K., Jha, R. "Reliable high-rate bridge monitoring using dense wireless sensor arrays," *The 6th International Workshop on Structural Health Monitoring*, 11-13 September 2007, Stanford, CA.