COVER SHEET

Title: *Field Validation of Flexure-Based Mobile Sensing Nodes on a Space Frame Bridge.*

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ABSTRACT

This research investigates the field validation of flexure-based mobile sensing nodes developed for structural health monitoring (SHM). Each mobile sensing node is a miniature robot that can carry sensors and automatically navigate on a steel structure. The flexible body design of the mobile sensing node allows it to negotiate with sharp corners on the structure. Multiple mobile nodes then form an organic mobile sensor network that can search for potential structural damage. Our previous research has investigated the performance of the mobile sensing nodes through laboratory experiments. The mobile sensor network was able to identify minor structural damage, illustrating a high sensitivity in damage detection that is enabled by the flexible deployment of the mobile sensing nodes. This paper extends the investigation into field study with a space frame bridge. Under wireless control command, multiple mobile and tetherless sensing nodes navigate autonomously to different sections of the steel bridge, for measuring structural vibrations at high spatial resolution. Using a small number of mobile sensing nodes, detailed modal characteristics of the bridge are identified.

INTRODUCTION

In order to improve the safety assessment for civil structures, extensive research has been performed in the field of structural health monitoring (SHM). An SHM system measures structural responses and identifies the onset of potential structural damage. Traditionally, coaxial cables are used to transmit sensor data. In recent years, various academic and industrial wireless sensing prototypes have been developed and validated in order to reduce the high cost of cable-based structural monitoring systems [1].

As a transformative change to wireless sensing, mobile sensing systems containing mobile sensing nodes can offer flexible system architectures with adaptive

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spatial resolutions and very little human effort [2]. In various applications, efforts have been made by incorporating mobility into traditional sensors. For example, a beam-crawler has been developed for wirelessly powering and interrogating battery-less peak-strain sensors; the crawler moves along the flange of an I-beam by wheels [3]. A robot able to crawl on a 2D surface was developed for visually inspecting aircraft exterior; the robot used ultrasonic motors for mobility and suction cups for adherence [4]. In order to inspect the inner casing of ferromagnetic pipes with complex-shaped structures, a compact robot with two magnetic wheels in a motorbike arrangement has been developed [5]; the robot can slightly lift off the wheel in order to negotiate concave edges. In addition, a remotely-controlled model helicopter has been demonstrated for charging and communicating with wireless sensors [6].

Nevertheless, researchers have rarely explored mobile sensor network with dynamic configurations for SHM purpose. Most recently, Lee *et al*. developed a flexure-based mobile sensing node [7], which is capable of attaching/detaching an accelerometer onto/from steel structural surface. Meanwhile, this flexure-based mobile sensing node has the potential to fulfill functions of negotiating in complex steel structures with narrow sections and high abrupt angle changes. Guo *et al*. conducted further mechanical analysis on the compliant mechanism of the flexure-based mobile sensing node [8]. Zhu *et al*. investigated the damage detection performance of the mobile sensing nodes through laboratory experiments [9]. The mobile sensor network was able to identify minor structural damage, illustrating a high sensitivity enabled by the flexible deployment of the mobile sensing nodes.

This paper investigates the field deployment of the flexure-based mobile sensing nodes on a pedestrian space frame bridge. Under wireless control command, multiple mobile sensing nodes navigate autonomously to different sections of the steel bridge, for measuring hammer impact and ambient vibrations at high spatial resolution. Using a small number of mobile sensing nodes, detailed modal characteristics of the bridge are successfully identified. The paper begins with the description of the space frame bridge and experiment setup. The modal identification results using the mobile sensor data are presented and compared among two excitation scenarios, i.e. hammer impact and ambient excitation. Finally, a summary and discussion are provided.

BRIDGE DESCRIPTION AND EXPERIMENTAL SETUP

The testbed pedestrian steel bridge (Figure 1) is located on Georgia Tech

Figure 1. Picture of the space frame bridge on Georgia Tech campus.

campus, connecting the Manufacturing Research Center (MARC) and the Manufacturing Related Disciplines Complex (MRDC). The bridge consists of eleven chord units, each unit 9 ft. long. The length, width and height of the bridge are 99 ft., 7 ft., and 9 ft., respectively. The frame members are made of square tubes with cross section dimension of 6 in. × 6 in. × 3/8 in. Diagonal bracing members are used in two vertical side planes and the horizontal planes (top and bottom) of the frame for enhancing structural stiffness. Hinge connections are adopted at the supports on the MARC side, and roller connections at the MRDC side.

The flexure-based mobile sensing nodes used in this study are capable of navigating on a steel structure as well as attaching/detaching an accelerometer on/from structural surface. The design and implementation of the mobile sensing node can be found in Lee *et al*. [7] and Zhu *et al*. [9]. The accelerometer (Silicon Designs 2260-010) used in this study has a frequency bandwidth of 0-300 Hz. The measurement range is ±2g, and the sensitivity is 1V/g, where 'g' is gravitational acceleration. In order to capture low-amplitude vibrations, e.g. due to ambient excitation, a low-noise high-gain signal conditioning module is equipped on each mobile sensing node [10]. The signal conditioning module consists of a high-pass filter with a cutoff frequency of 0.014Hz and a low-pass 4^{th}-order Bessel filter with a cutoff frequency of 25Hz. The amplification gain of the signal conditioning module can be easily adjusted to ×2, ×20, ×200, or ×2,000.

Four mobile sensing nodes are used in this experiment for navigating on the top plane of the frame. The mobile sensing nodes start from the inclined members at one side of the bridge (Figure 2(a)), and move to the 1^{st} measurement configuration (Figure 2(b)). A total of five measurement configurations are adopted for the mobile sensing nodes. As shown in Figure 3(a), each configuration consists of four measurement locations. Locations on the south plane of the frame are marked with letter 'S', and locations on the north plane are marked with letter 'N'. The measurement configurations for the mobile sensing nodes do not contain locations 5S and 5N, where static wireless sensing nodes are mounted as reference nodes for assembling mode shapes of the bridge. At each measurement configuration, the mobile sensing nodes attach accelerometers onto the structural surface, and measure structural vibrations in the vertical direction. After finishing the measurement at the 1^{st} configuration, the mobile sensing nodes move to the 2^{nd} configuration, and so on, until

(a)

(b)

Figure 2. Pictures of four mobile sensing nodes navigating on the space frame bridge: (a) The mobile sensing nodes start from the incline members; (b) The mobile sensing nodes arrive at the 1^{st} measurement configuration.

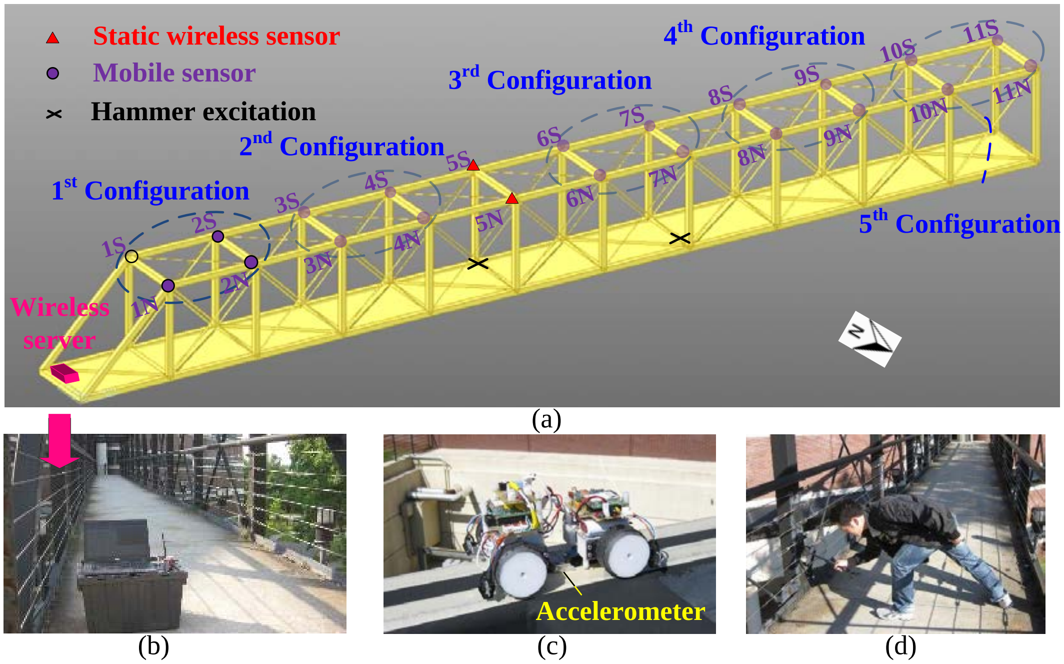

Figure 3. Experimental setup for the mobile sensor testing: (a) 3D illustration of five measurement configurations for the mobile sensing nodes; (b) A laptop as the wireless server; (c) A mobile sensing node attaches an accelerometer onto the structural surface; (d) A hammer impact being applied.

they finish measurement at the 5th configuration. The mobile sensing nodes are wireless controlled by a laptop server, which is located on the floor level at one side of the bridge. Figure 3(c) shows a mobile sensing node that has attached an accelerometer onto the structural surface for vibration measurement.

EXPERIMENTAL RESULTS

This section first presents the mobile sensor measurement and modal identification results from hammer impact data, followed by those from ambient vibration data. Finally, the modal analysis results from hammer impact data and ambient vibration data are compared.

Hammer impact test

Hammer impact test is first conducted. Two locations are chosen for applying individual hammer impact on the floor, which are directly below locations 5S and 7N in Figure 3(a). After the four mobile sensing nodes arrive at each configuration, hammer impact is first applied at the floor below 5S for data collection, and then another impact is applied below 7N. Figure 3(d) shows the picture of a hammer impact being applied at the location below 5S. The impact hammer is a 3-lb hammer manufactured by PCB Piezoelectronics. The impact head allows for different tips to be affixed to the end, to vary the frequency range of the input. A soft plastic tip is used in this study. The amplification gain of the signal conditioning module is set to $\times$20 during hammer test. The sampling rate is set to 200Hz.

Figure 4 presents example acceleration time histories recorded at locations 5S and 9N, as well as the corresponding frequency spectra plots when the hammer impact is applied on the floor below location 5S. Figure 5 presents example acceleration time histories recorded at same locations, as well as the corresponding frequency spectra plots when the hammer impact is applied on the floor level location 7N. The eigensystem realization algorithm (ERA) is applied to the mobile sensor data for extracting modal characteristics at each configuration [11]. The mode shapes of the entire bridge are assembled through the reference nodes with wireless static sensors. Figure 6 and Figure 7 show the first three mode shapes of the space frame bridge when the hammer impact is applied on the floor below locations 5S and 7N, respectively. Comparison between Figure 6 and Figure 7 shows that the natural frequencies and mode shapes extracted from mobile sensor data with different hammer impact locations are quite close. The first vertical mode shape shows all nodes moving along one direction, which is expected for such a simply supported bridge. With increasing complexities, other modes also agree with typical behavior of this type of structures.

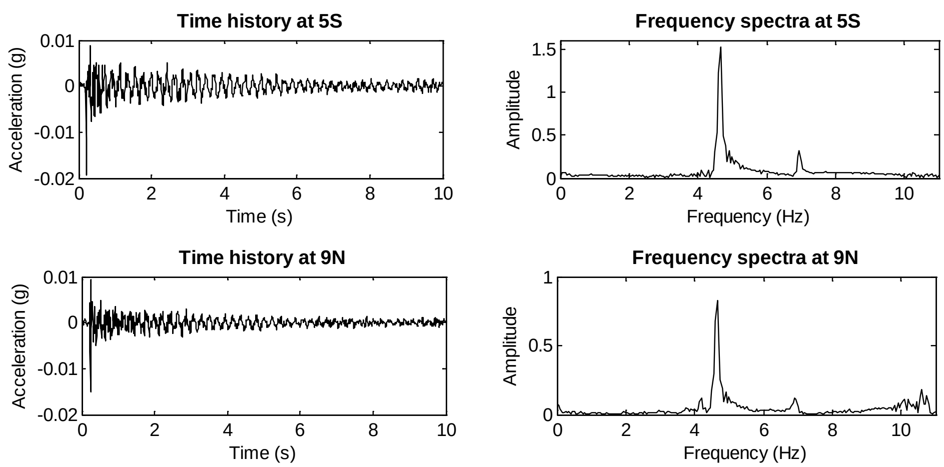

Figure 4. Example vibration records and corresponding frequency spectra when the hammer impact is applied on the floor below location 5S.

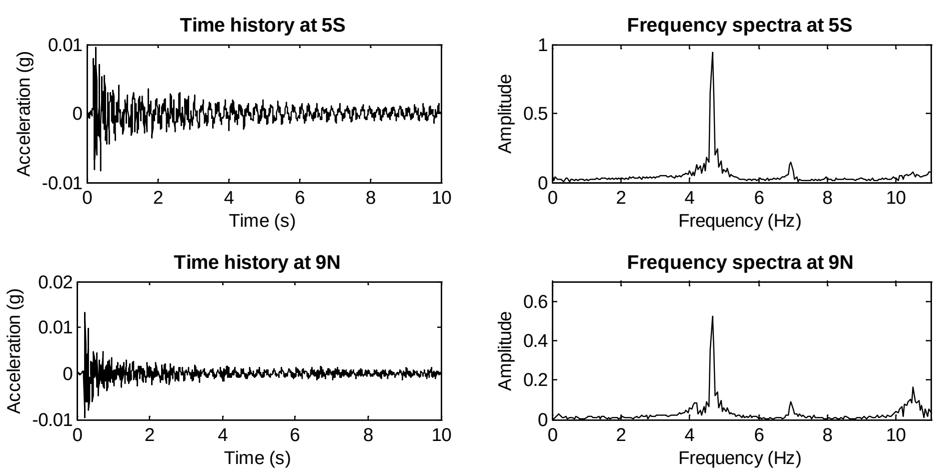

Figure 5. Example vibration records and corresponding frequency spectra when the hammer impact is applied on the floor below location 7N.

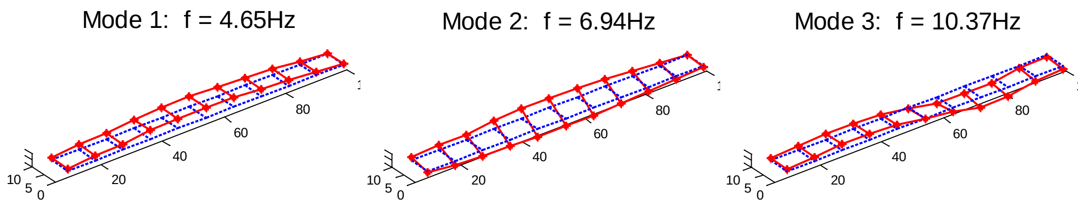

Figure 6. First three mode shapes of the bridge extracted from mobile sensor data when the hammer impact is applied on the floor below location 5S.

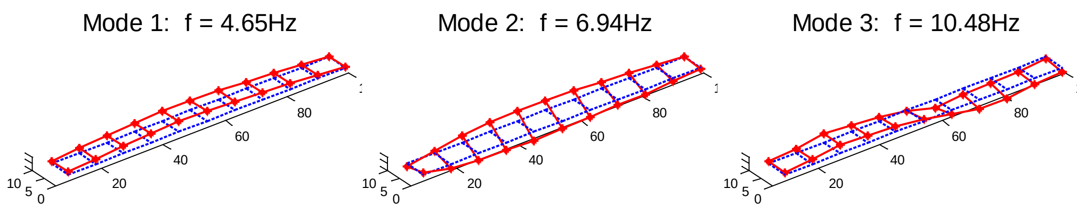

Figure 7. First three mode shapes of the bridge extracted from mobile sensor data when the hammer impact is applied on the floor below location 7N.

Ambient vibration test

During the ambient vibration test, 10 minutes of data is collected for each mobile measurement configuration. The amplification gain of the signal conditioning module is set to ×200 during ambient vibration test, and the sampling rate is set to 100Hz. Figure 8 presents example ambient vibration time histories recorded at locations 5S

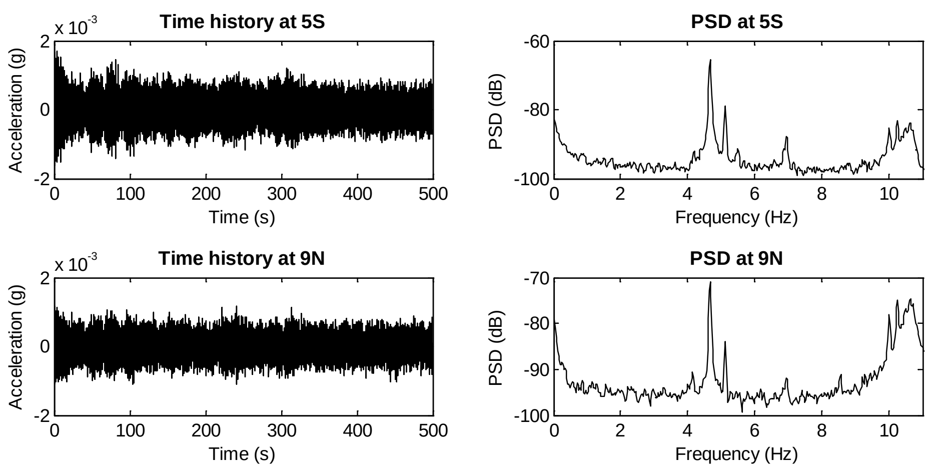

Figure 8. Example ambient vibration records and corresponding power spectral density (PSD) plots.

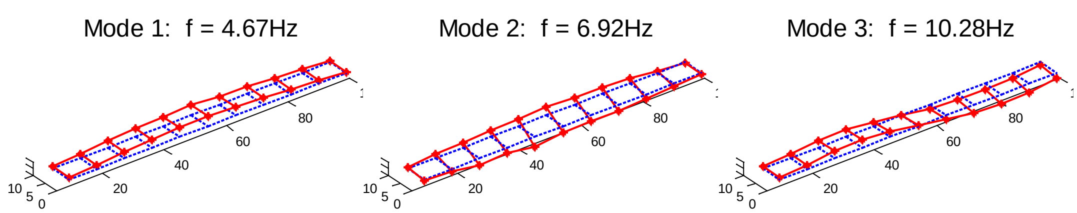

Figure 9. First three mode shapes of the bridge extracted from ambient vibration data collected by the mobile sensing nodes.

and 9N, as well as the corresponding power spectral density (PSD) plots. The natural excitation technique (NExT) is applied to the mobile sensor data to extract modal characteristics at each configuration [12]. Similarly, the mode shapes for the entire bridge are assembled through the reference nodes. Figure 9 shows the first three mode shapes of the space frame bridge from ambient vibration data collected by the mobile sensing nodes.

Modal analysis comparison

The first three natural frequencies extracted from hammer impact test and ambient vibration data are summarized in Table I. The frequency differences between different excitation scenarios are very small. To evaluate the differences in mode shapes, the modes extracted from ambient vibration data are used as the reference modes, and the modal assurance criterion (MAC) value is calculated for mode shapes extracted from hammer impact data:

$$\mathrm{MAC}_i = \frac{(\phi_{H,i}^{\mathrm{T}}\phi_{A,i})^2}{(\phi_{H,i}^{\mathrm{T}}\phi_{H,i})(\phi_{A,i}^{\mathrm{T}}\phi_{A,i})} \tag{1}$$

where $\phi_{H,i}$ and $\phi_{A,i}$ denote the *i*-th mode shape extracted from hammer impact data and ambient vibration data, respectively; MAC_i represents the *i*-th MAC value between the *i*-th mode shapes. Note that if the mode shapes $\phi_{H,i}$ and $\phi_{A,i}$ are close to each other, MAC_i should be close to 1. The MAC values shown in Table I are all greater than 0.9. This again confirms that the mode shapes extracted from mobile sensor data in various excitation scenarios are reasonably close. Therefore, it can be concluded that the mobile sensing system is capable of providing consistent and reliable sensor data with high spatial resolution.

SUMMARY AND DISCUSSION

Exploratory work harnessing mobile sensor networks for SHM is presented in this paper. A four-node mobile sensor network is used to navigate autonomously to different sections of a steel bridge, for measuring vibrations due to hammer impact and ambient excitation at high spatial resolution. To achieve higher signal-to-noise ratio for the mobile sensor, a low-noise high-gain signal conditioning module is equipped on each mobile sensing node to filter and amplify accelerometer signal. Modal analysis is successfully conducted using the mobile sensor data. The first few

Table I. Comparison of modal characteristics extracted from hammer impact and ambient vibration data.

Mode	Natural frequencies (Hz)			MAC values	
	Hammer impact below 5S	Hammer impact below 7N	Ambient vibration	Hammer impact below 5S	Hammer impact below 7N
1	4.65	4.65	4.67	0.99	0.99
2	6.94	6.94	6.92	0.95	0.94
3	10.37	10.48	10.28	0.94	0.95

natural frequencies and corresponding mode shapes are extracted and compared using mobile sensor data from various excitation scenarios. It is shown that modal characteristics extracted from the mobile sensor data are consistent and reliable using either hammer impact or ambient excitation. Future work will be conducted to improve the mobile sensing system for navigating on more complicated real-world structures. In addition, a mobile excitation node can be developed for applying small-magnitude impact forces to one local area of a structure.

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