Validation of a wireless traffic vibration monitoring system for the Voigt Bridge

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ABSTRACT: Recently, a variety of wireless structural health monitoring systems have been demonstrated as viable substitutes for traditional high-cost tethered monitoring systems. In this study, a prototype wireless sensing system is deployed upon the Voigt Bridge (La Jolla, CA) to validate its performance against a cabled monitoring system. Using 20 wireless sensors deployed over two spans of the bridge superstructure, acceleration time histories and their corresponding Fourier transforms collected from traffic-induced vibration suggest excellent correlation with those obtained from the tethered system. Embedded data processing is highlighted in this study with operational deflection shapes of the bridge identified by the wireless sensor network using embedded peak picking algorithms. Along with the cabled monitoring system is a video camera installed to continuously record bridge traffic. Video streams allow the input to the structural system to be quantified and directly linked to the output bridge response.

Keywords: wireless sensors, structural health monitoring, traffic monitoring, video streaming.

1 INTRODUCTION

Deteriorating civil infrastructures (*i.e.* buildings, bridges, roadways, lifelines, among others) around the world have warranted the need for high performance sensors for automated structural health monitoring (SHM). In fact, in the United States alone, $91 billion dollars are spent annually to maintain existing structures to meet current design standards (Njord & Meyer 2006). As a result, over the past several decades, researchers have adopted traditional tethered sensing systems for monitoring structural performance. Unfortunately, the high costs to install and maintain extensive networks of coaxial cables that connect sensors to the data acquisition system (DAQ) have retarded commercial adoption. It is estimated that each sensor channel instrumented on a large building or long-span bridge costs on the order of thousands of dollars, rendering dense sensor instrumentations impractical (Celebi 2002).

Due to the aforementioned high costs and intensive labor required for installing and maintaining cabled monitoring systems, many researchers have developed a variety of academic and commercial wireless sensor prototypes for SHM over the past 10 years (Straser & Kiremidjian 1998; Spencer et al. 2004; Lynch & Loh 2006). With costs on the order of a hundred dollars per sensor node, a dense sensor instrumentation strategy is viable for large civil structures. Furthermore, densely distributed wireless sensors permit component-level SHM (*i.e.* monitoring of local strain, cracking, and corrosion processes). As opposed to permanently installing one type of sensor (*e.g.* accelerometers) to the structure of interest, a variety of sensors can be connected to a single wireless sensing node for measuring different response parameters.

While wireless sensors are highly cost-competitive when compared to tethered monitoring systems, their real merit lies within their embedded computational capabilities. In traditional tethered monitoring systems, an enormous amount of data is continuously collected and transmitted to a centralized data repository. When multiple sensing channels are employed, the amount of data streaming into the DAQ requires high-performance computational resources to process and store all of the data. However, when power-efficient computational resources (*e.g.* microcontrollers) are coupled with wireless sensing nodes, they can locally process data prior to transmitting them back to the DAQ (Lynch 2007). By distributing computational resources throughout the sensor network, the DAQ computational demand is significantly reduced, thereby allowing real-time system identification and damage detection to be performed.

In this study, a prototype wireless sensing system is instrumented on the Voigt Bridge (La Jolla, CA) to demonstrate and compare its embedded computational performance against a tethered monitoring system permanently installed by Prof. Elgamal and his research group at UCSD (Fraser et al. 2006). An innovative feature of their monitoring system is that it includes a high-resolution video camera that can track vehicle traffic in real-time. While processing of acceleration time history records by the wireless sensors can be used to roughly approximate bridge traffic conditions, this study leverages the high-resolution video data of the tethered monitoring system to provide direct quantitative information on the bridge loading.

This paper begins by describing the wireless sensor hardware and software design followed by a description of signal conditioning circuitry that is used to amplify and filter raw sensor data. Then, preliminary time history response data obtained from ambient traffic monitoring is compared with those collected by the cabled system to validate wireless sensor performance. Embedded data processing is employed by each wireless sensor to calculate Fourier response spectra corresponding to the bridge response. In addition, operational deflection shapes are calculated by the wireless monitoring system using different input loads (*i.e.* modal hammer, cars, and truck). The wirelessly recorded bridge response is time synchronized to the camera video stream to offer insight to the cause and effect relationship between traffic and bridge responses.

2 WIRELESS SENSING SYSTEM

2.1 *Wireless Sensing Node Hardware*

In general, wireless sensor hardware can be categorized into three functional modules, namely data acquisition, computation, and wireless communications (Wang et al. 2005). First, the DAQ subsystem digitizes analog sensors data (*i.e.* from accelerometers, strain gauges, velocity meters, among others) using a 4-channel 16-bit analog-to-digital (A/D) converter (Texas Instruments ADS8341). Using this A/D converter, a maximum sample rate of 100 kHz can be achieved. Upon data digitization, the sampled data is locally processed within the 8-bit Atmel ATmega128 microcontroller (which is the center of the computational core). Embedded firmware such as FFT (fast Fourier transform), auto-regressive time series modeling, and other system identification tools stored onboard the microcontroller can be executed (Lynch 2007). Since 4 kB of on-chip data memory is typically insufficient for recording long time histories, an additional 128 kB memory bank (Cypress CY62128B) is also included with the hardware design.

Whether one wishes to stream sampled data in real-time or to transmit computed results at the end of each sampling period, a 900 MHz MaxStream 9XCite wireless transceiver is employed to wirelessly transmit the data to a base station. With a maximum transmission range of 300 m outdoors and 90 m indoors, this wireless transceiver can accommodate most sensor instrumentation layouts in small and large civil structures. Furthermore, the advantage of using this radio is that it only consumes 20 μA while standing-by and 55 mA and 35 mA while transmitting and receiving data, respectively.

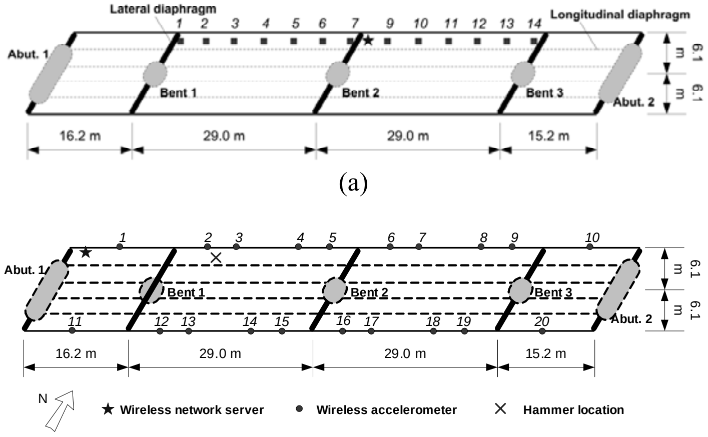
2.2 *Signal Conditioning Module*

Since typical ambient structural vibrations are of low amplitude, such data is susceptible to corruption from electrical noise within the wireless sensor hardware. Therefore, an additional signal conditioning module is incorporated to amplify (up to 20 times) and filter the analog output of accelerometers interfaced to wireless sensors (Lynch et al. 2006). Here, a high-pass resistor-capacitor (RC) filter with a cutoff frequency of 0.02 Hz and a low-pass fourth-order Bessel filter with a cutoff frequency of 25 Hz are combined to formulate a band-pass filter. Since most structural fundamental modes of vibrations are within this range, low- and high-frequency noise can be removed to enhance the quality of sensor data collected.

2.3 *Architectural Design*

In this study, a simple star-topology sensor network is employed, which consists of one wireless receiver connected to a DAQ (*e.g.* laptop computer) with multiple wireless sensing nodes communicating data to the DAQ. While this network architecture resonates with those of tethered systems, one of the significant advantages of using wireless sensors is that computational resources can be allocated to each node so as to achieve scalable distributed processing across the network. In this study, each sensing node is coupled with an embedded microcontroller capable of locally processing data from any or all of its sensing channels (four channels). Furthermore, since these wireless sensors are equipped with high-performance wireless transceivers with an outdoor operational range of 300 m, a star-topology sensor network is suitable for small- and medium-scale civil infrastructures. Last but not least, wireless sensors allow the flexibility to reconfigure sensor locations and network topology.

Figure 1. A photograph of the Voigt Bridge crossing Interstate 5 taken from the western abutment. The bridge itself experiences low levels of vehicle and pedestrian traffic during the experimental phase of this study.



(a)

(b)

Figure 2. A schematic illustrating the plan view of the bridge with 20 wireless sensors instrumented on the middle two spans of the Voigt Bridge (wireless sensors are placed directly over the existing tethered monitoring system): (a) Configuration 1; (b) Configuration 2.

3 FIELD VALIDATION TESTING

3.1 *Voigt Bridge*

The Voigt Bridge, located at the University of California, San Diego (UCSD) campus, is a four-span concrete box girder bridge crossing Interstate 5, as shown in Figure 1. The total bridge span is approximately 89.4 m with a skew angle of 32°. To prevent any experimental error during wireless vibration monitoring, accelerometers and wireless sensor nodes are installed adjacent to the preexisting cable-based monitoring system (Fraser et al. 2006). In this study, two accelerometer types are used; at most sensor locations, PCB Piezotronics 3801 accelerometers are used for both the cabled and wireless systems, while at the remaining locations, Crossbow CXL01LF1 and CXL02LF1Z accelerometers are used for the cabled and wireless systems, respectively.

In total, 20 wireless sensor nodes each coupled with a signal conditioning module are instrumented throughout the middle two main spans of the bridge as shown in Figure 2a. Provided that the wireless sensors are not tethered, their installation locations can be easily changed as testing progresses. For example, the monitoring system layout in the Voigt Bridge has been changed part way through testing to a second configuration as shown in Figure 2b.

3.2 *Ambient Vibration Monitoring and Validation*

Upon collecting ambient bridge vibrations using both systems (the sampling rate of the cabled system is 1 kHz while that of the wireless system is 100 Hz), the time histories and computed FFT spectra are overlaid as shown in Figures 3 and 4, respectively. It can be seen from both the time- and frequency-domain data that minimal differences can be

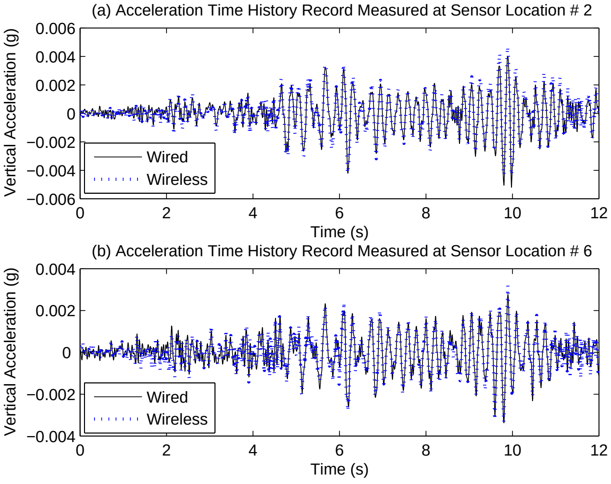


Figure 3. Comparison between acceleration time histories measured by the wireless and tethered monitoring systems at: (a) sensor locations #2 and (b) location #6 (Configuration 1).

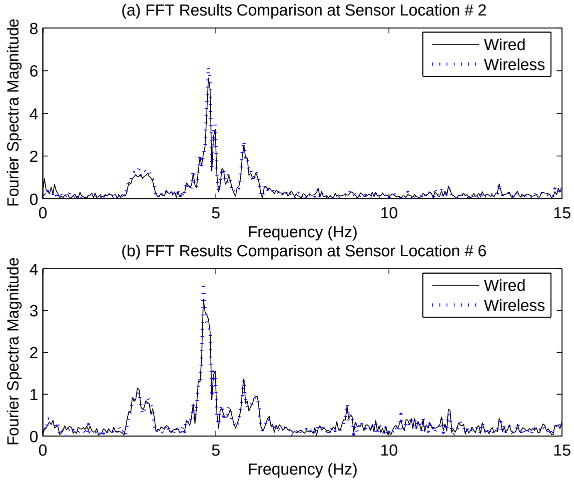


Figure 4. Comparison between FFT results computed by the wireless and tethered monitoring system at: (a) sensor location #2 and (b) location #6 (Configuration 1).

Figure 5. A photograph of the high-performance Sony XCD-X710CR video camera installed on a light post located at the western abutment of the Voigt Bridge. The video monitoring system records bridge traffic continuously and stores data at a centralized data repository (Fraser et al. 2006).

Figure 6. A photograph of an UCSD bus crossing the bridge. It can be seen that the Voigt Bridge only experiences low levels of traffic, where usually, only one vehicle passes the bridge at a time.

observed. Although these results only represent one of the many tests conducted during the experimental phase of this study, other results show comparable similarity between the cabled and wireless monitoring systems.

In Figure 4, the overlays between the Fourier spectra obtained from the cabled and wireless systems are presented. It should be noted that the FFT results for the cabled system are computed offline (after testing) while the FFT results from the wireless system are computed locally at each sensor node and then transmitted to the base station. The Cooley-Tukey algorithm of the FFT has been embedded in each wireless sensor so it can locally transform time history data to the frequency domain (Lynch 2007). It can be seen from Figure 4 that the frequency response functions coincide quite nicely, thus demonstrating the wireless system can perform at a level equivalent to that of most commercial tethered monitoring systems.

4 VIDEO-ENHANCED WIRELESS TRAFFIC MONITORING

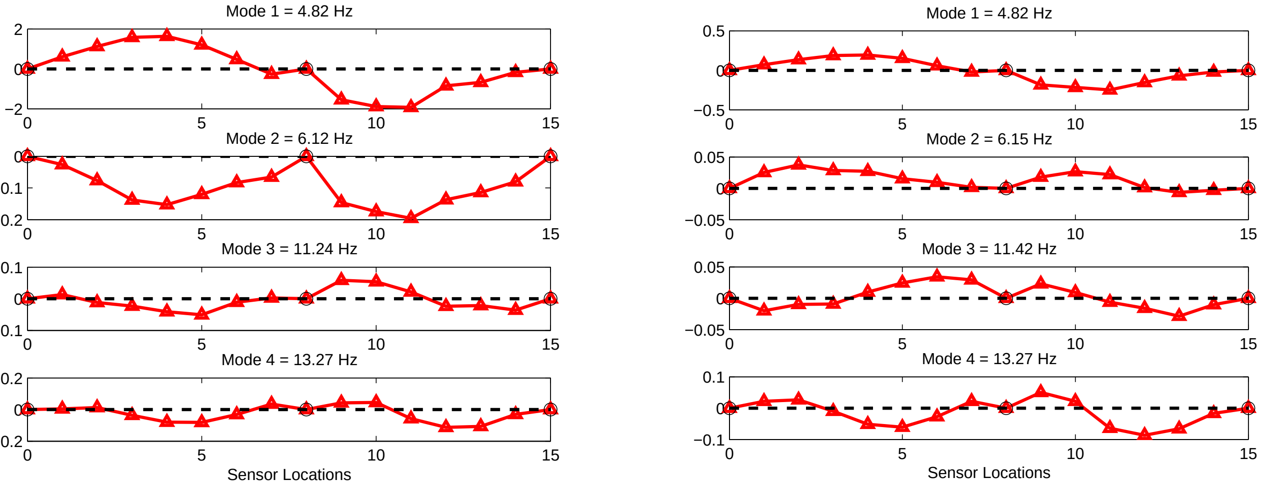
One of the advantages of installing a wireless monitoring system on the Voigt Bridge is that a high-performance Sony XCD-X710CR IEEE 1394 digital video camera (Fig. 5) is in-place to monitor vehicle traffic (Fraser et al. 2006). As opposed to only monitoring long-term global vibration characteristics of the bridge without information on the traffic load, measured bridge responses can now be tied back to the recorded video which supplies physical traffic loading at all times. For instance, if sudden traffic-induced damage is detected by the monitoring system, it can be traced back to the particular vehicle which caused the damage (*e.g.* overweight truck). Furthermore, the recorded video can be used to determine vehicle velocities passing over the bridge (Fraser et al. 2006).

Located at the west abutment of the Voigt Bridge, this video camera continuously records all vehicular traffic at 30 frames per second and stores the data at a centralized data repository (Fraser et al. 2006). It should be noted that the video streams are time-synchronized with the array of accelerometers permanently installed in the bridge. While the recorded video supplies detailed information regarding the specific time and type of vehicles passing over the bridge, the data itself requires significant storage space and processing. Extraction of traffic information is accomplished by using automated image processing techniques or having a trained specialist review the recorded video.

In this study, the wireless monitoring system is employed to measure bridge vertical vibration over long periods of time. Upon time synchronization with the recorded video data, one can physically link the measured induced bridge vibration to the exact excitation source (*i.e.* car, bus, truck, or modal hammer). Using different vehicle-induced bridge vibrations (*e.g.* Fig. 6), the operational deflection shapes (ODS) corresponding to the first few modes of vibration are determined for various excitation sources manually identified from the video data.

4.1 *Operational Deflection Shapes Analysis*

Using the first wireless sensor layout (Fig. 2a), the sensors are commanded to record acceleration time histories as well as to perform FFT analyses onboard each sensing node before transmitting the results to the wireless server. To further illustrate the functionality of the wireless sensors' computational capabilities, an embedded peak-picking algorithm at each sensor node is employed to identify the bridge's modal frequencies. Upon determining the first four modal frequencies, the imaginary components of the Fourier spectra are transmitted to the wireless server. Then, the ODSs for the first four primary deflection modes can be obtained by plotting the imaginary component of the FFT results for



(a) (b)

Figure 7. (a) The operational deflection shapes for the first four modes of deflection as obtained using acceleration time history data collected by the wireless monitoring system due to a modal hammer striking the bridge deck and (b) car traffic.

every sensor at each corresponding modal frequency.

Figure 7 presents the ODSs due to a modal hammer blow and traffic (three consecutive cars) excitation. It should be noted that the time-synchronized video data (Fraser et al. 2006) allows one to identify the bridge excitation source. Since the modal hammer and traffic loading represent broadband excitation sources in the frequency domain, the first four primary mode shapes should be adequately excited and captured by the wireless sensing system. As expected, operational deflection shapes obtained from the modal hammer and traffic loading correspond well with one another (Fig. 7). However, the precise nature of the modes (*i.e.* flexural versus torsion) are difficult to quantify from the ODS results since the wireless sensors in the first configuration (Fig. 2a) are installed in a straight line across one side of the bridge.

In response to this limitation, the wireless monitoring system is reconfigured to a second configuration (Fig. 2b) that is well-suited for observing the flexural and torsional nature of the bridge modes. With wireless sensors evenly spaced on both sides of the bridge, modal hammer blows are once again delivered to the deck of the bridge in the vicinity of sensor location #3. The ODSs calculated by the wireless monitoring system are shown in Figure 8.

It can be easily identified that ODS #1 (4.9 Hz) and #2 (6.2 Hz) represent flexural bending modes. This is confirmed by the modes presented in Figure 8. ODS #3 (8.01 Hz) is clearly a torsion mode that is not identified using the first network topology (Fig. 2a). However, ODS #4 (11.6 Hz) observed by both systems is primarily flexural. The last operational deflection shape (13.3 Hz) identified during the first network topology (Fig. 2a) is not observed during the second configuration.

4.2 *Wireless Traffic Monitoring*

The Voigt Bridge is continuously monitored by the tethered monitoring system using both accelerometers and the video camera. The video camera allows the precise nature of traffic loading to be identified. In this study, camera streams are time synchronized to the acceleration response data collected by the wireless and wired monitoring systems. As shown in Figure 9, the vertical acceleration response of the bridge is presented for five sensor locations (locations #1, 3, 6, 9 and 12 in the first network configuration as shown in Fig. 2a). The response presented is due to one 2-axle delivery truck driving across the bridge in the eastern direction. The video camera continuously collects video of the bridge at a rate of 30 frames per second. Because the video is synchronized with the acceleration data, the video captured at 2, 6 and 10 second is presented in Figure 9. Since the precise length of the bridge is known, the speed of the truck can be estimated by taking the time difference between when the truck first enters and exits the bridge (obtainable from time-stamps on the video frames). In this example, the truck is traveling at approximately 27 km/h (17 mph).

5 CONCLUSIONS

In this study, a prototype wireless sensor network is deployed upon the Voigt Bridge to monitor traffic-induced bridge vibrations. Using a dense network of 20 wireless sensors each coupled to a signal conditioning module to amplify and band-pass the accelerometer output, the recorded time histories correspond accurately with those obtained by the cable-based monitoring system. Furthermore, upon comparing the FFT results computed onboard each sens-

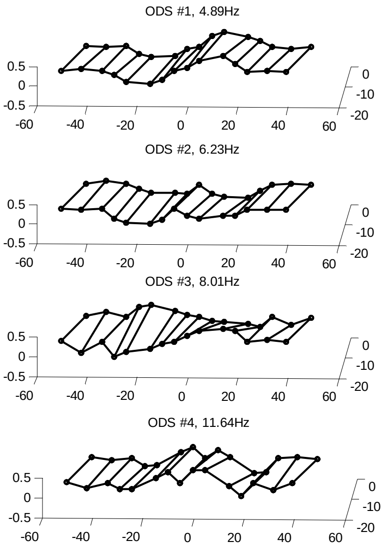


Figure 8. Four operational deflection shapes identified by wireless monitoring system in Configuration 2 (Fig. 2b).

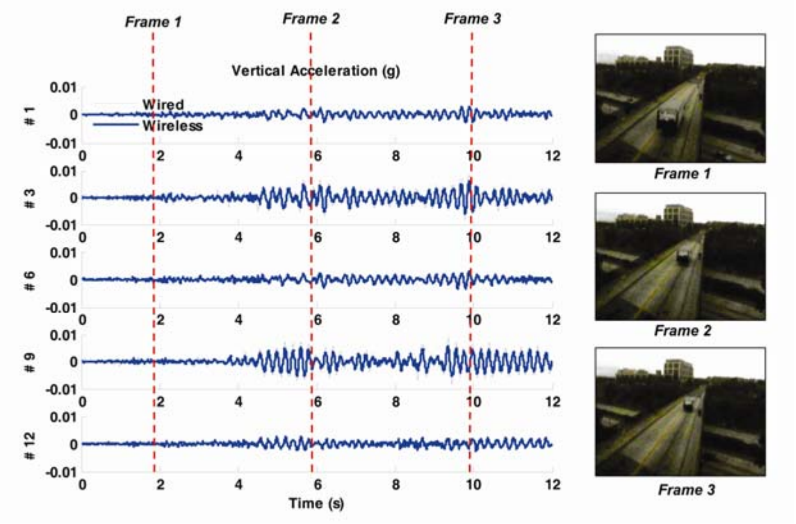


Figure 9. Recorded acceleration time histories (wired and wireless) at four sensor locations as a delivery truck transverses the bridge. Video frames corresponding to three times of loading are presented while showing the truck location at each instant.

ing unit to those measured and computed offline by the cabled system, the response correlates well with little to no discrepancies. In addition, using the FFT results, operational deflection shapes for the first four fundamental modes of vibration of the bridge have been presented. The ODSs obtained suggest the bridge is primarily dominated by flexural and torsional bending modes.

While it is advantageous to validate the wireless sensing system against a pre-installed permanent tethered SHM system, another advantage of installing wireless sensors on the Voigt Bridge is that a high-performance video camera is also installed to monitor bridge traffic continuously. By correlating recorded acceleration time histories measured by the wireless sensing system to the video data, the influence of traffic on the bridge response can be directly linked.

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