Long-Term Assessment of an Autonomous Wireless Structural Health Monitoring System at the New Carquinez Suspension Bridge

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ABSTRACT

A dense network of sensors installed in a bridge can continuously generate response data from which the health and condition of the bridge can be analyzed. This approach to structural health monitoring the efforts associated with periodic bridge inspections and can provide timely insight to regions of the bridge suspected of degradation or damage. Nevertheless, the deployment of fine sensor grids on large-scale structures is not feasible using wired monitoring systems because of the rapidly increasing installation labor and costs required. Moreover, the enormous size of raw sensor data, if not translated into meaningful forms of information, can paralyze the bridge manager's decision making. This paper reports the development of a large-scale wireless structural monitoring system for long-span bridges; the system is entirely wireless which renders it low-cost and easy to install. Unlike central tethered data acquisition systems where data processing occurs in the central server, the distributed network of wireless sensors supports data processing. In-network data processing reduces raw data streams into actionable information of immediate value to the bridge manager. The proposed wireless monitoring system has been deployed on the New Carquinez Suspension Bridge in California. Current efforts on the bridge site include: 1) long-term assessment of a dense wireless sensor network; 2) implementation of a sustainable power management solution using solar power; 3) performance evaluation of an internet-enabled cyber-environment; 4) system identification of the bridge; and 5) the development of data mining tools. A hierarchical cyber-environment supports peer-to-peer communication between wireless sensors deployed on the bridge and allows for the connection between sensors and remote database systems via the internet. At the remote server, model calibration and damage detection analyses that employ a reduced-order finite element bridge model are implemented.

Keywords: Structural health monitoring, wireless sensors, long-term monitoring, cyber-infrastructure, system identification

1. INTRODUCTION

As aging bridges in the United States undergo wear-and-tear deterioration, bridge owners must expend significant resources to vigilantly inspect and rehabilitate their inventory. In recent years, this task has become increasingly challenging due to reductions in the economic resources necessary to fund these efforts. The need to invest in bridge inspection and repair is necessary to avoid catastrophic failure of these critical infrastructure elements. The loss of human life and the long-term economic impact of a failed bridge can be enormous as was the case in Minnesota when the I-35 Bridge collapsed in 2007. Even the partial failure of a critical bridge component can represent an expensive management issue that can adversely affect bridge users for a long period of time. For example, the San Francisco-Oakland Bay Bridge experienced a failed eyebar in 2009 [1]. After detection, the bridge was closed for a short-period followed by nightly lane closures for 5 weeks as construction crews repaired the element. The issue also resulted in more frequent visual inspections of the bridge eyebars.

The current approach to bridge inspection largely relies on visual inspections conducted by professionally trained inspectors with years of experience. While this approach to bridge management has served the bridge engineering community well for many years, it is potentially not a scalable management approach as the inventory of bridges rapidly ages. In addition, the information obtained by visual inspections can contain a high degree of variability due to the subjectivity of the inspectors. In some cases, inspectors are required to conduct their visual inspection in unpleasant

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work environments that make the inspection process more challenging. The emergence of low-cost sensors and data acquisition systems has now made permanently installed monitoring systems a possibility for bridges. The availability of real-time data from a bridge monitoring system can aid bridge owners in more objectively evaluating the conditions of their structures. The vast majority of monitoring systems deployed on operational bridges have been based on the use of tethered (*i.e.*, wired) system architectures. However, the installation of tethered sensors, specifically their extensive wiring, can be costly and labor intensive. In addition, the coaxial wires can be vulnerable to physical failure. In response to these limitations, wireless communication technologies have been proposed for future bridge monitoring systems. Wireless bridge monitoring systems provide bridge owners with the option of making a smaller initial investment (largely because wires have been eradicated) while still offering the benefits gained from long-term bridge monitoring. While wireless bridge monitoring systems have shown great promise, their long-term reliability in real bridges is not yet well explored with only a limited number of efforts reported in the literature [2, 3]. Other major impediment in applying wireless sensors in long-span bridge systems is the lack of viable power sources that can sustain operations for long periods of time (*e.g.*, years, decades) without requiring the physical replacement of batteries. The continuous operation of a wireless bridge monitoring system requires the use of low-power hardware components coupled with an appropriate power harvesting technology (*e.g.,* solar cells, miniature wind turbines, vibration power harvester).

In this study, a low-power wireless sensor network constructed from the *Narada* wireless sensing unit is adopted to serve as the building block of a wireless bridge monitoring system. To create a wireless monitoring system with enhanced longevity in the field, a power management system based on solar energy is adopted. An assessment of the long-term performance of the proposed wireless monitoring system is ongoing at the New Carquinez Bridge (NCB). The wireless sensor network is coupled with a multi-layered cyber-environment which automates the timed collection of sensors data, communicates data via a secure cellular connection, stores data with regular backups, and offers access to end-users. To highlight the quality of the data collected, the raw sensor data collected by the installed wireless monitoring system is used for system identification of the bridge. Finally, the collected bridge information is used to update a finite element model of the bridge.

2. AUTONOMOUS WIRELESS BRIDGE HEALTH MONITORING SYSTEM

A wireless structural health monitoring system designed for long-span bridges should be autonomous and not require regular maintenance. In that spirit, this study explores the creation of hardened wireless monitoring system that can operate for long periods of time without human intervention. To provide the system with complete autonomy and to ensure the system is continuously checked for component failures, the wireless monitoring system installed in a bridge is part of a larger cyber-environment that manages the flow of data and information from the sensor to the end-user. The cyber-environment is hierarchically designed using two major tiers (Figure 1). In the lower tier, a network of low-power *Narada* wireless sensors is deployed within a bridge to collect bridge responses and environmental data continuously, on a schedule or on demand by system end users. Once data is collected, the *Narada* sensor network processes the raw sensor data using in-network data interrogation methods in order to consolidate it into a compact format. The *Narada* nodes on the lower tier then communicate that data through an on-site server to the upper tier via a third generation (3G) cellular network connection. The upper tier of the system architecture essentially wraps the lower tier into the complete cyber-environment. The upper tier supports two-way communication between the on-site *Narada* server and servers remotely located on the internet including a database server, an application server and a remote terminal server. The hierarchical design of the proposed wireless bridge monitoring system enables online system diagnosis (*i.e.,* to ensure the long-term durability of the monitoring system) and system reconfiguration (*e.g.,* change sample rate, modify collection schedule).

2.1 Lower Tier: Low-Power Wireless Sensor Network

The *Narada* wireless sensor nodes and the *Narada* data collection server (*i.e.,* base station) work as the primary building blocks of the lower tier of the monitoring system architecture. The *Narada* node is a low-power wireless sensor node designed explicitly for the monitoring of civil infrastructure systems and has been successfully used in many types of structures in the past [4]. The node features 16-bit digitalization of analog sensor data on 4 independent input channels at sample rates as high as 100 kHz. The core of the wireless sensor is an 8-bit microcontroller that is responsible for the overall node operation including the storage of sensor data. The maximum number of sampling points that can be saved in the core is limited by the node's 128kB static random access memory (SRAM) bank. The node's microcontroller core has an option to support the in-network processing (*i.e.*, on-board data interrogation coordinated between multiple

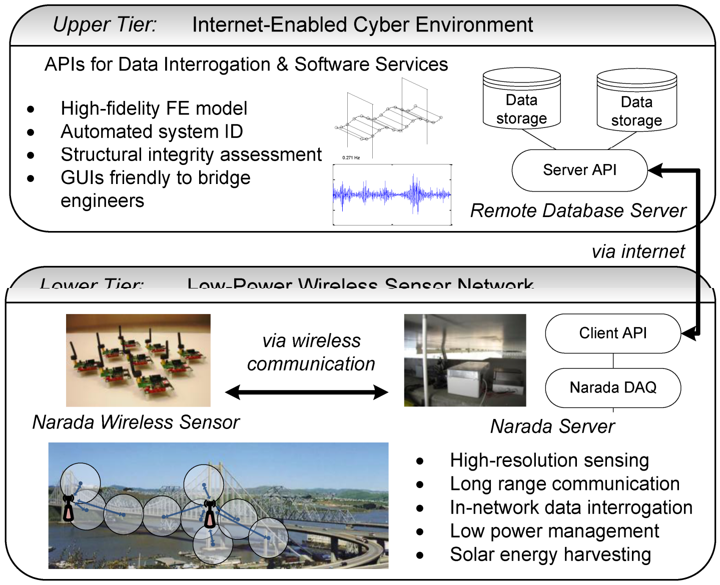


Figure 1. Architectural overview of the proposed two-tier wireless health monitoring system for bridges.

wireless nodes) of raw measurement data to reduce the size of the flow of data to be communicated. The node is also equipped with a wireless transceiver that adopts the 2.4 GHz IEEE 802.15.4 radio standard (Zigbee). The transceiver is designed with a power amplifier to boost the communication power of the node of long-range communication (*i.e.*, 700 m line-of-sight). Fully assembled, the nominal battery life of the *Narada* node is 40-45 hrs with a standard 5-AA battery pack. This life expectancy can be extended by 60% when using sleep mode (*i.e.*, the microprocessor of the *Narada* node is powered down). However, the battery life of the system is drastically extended by implementing a solar cell with each node (3.3W, 9V solid-state photovoltaic cell). The *Narada* wireless sensors are enclosed in a water tight enclosure to protect all of the electronics from the weather.

The basic function of the *Narada* server is to trigger data sampling in the wireless sensor network at a scheduled time and to synchronize the network based on beacon synchronization. The server also serves as the primary communication conduit for the flow of data from the *Narada* wireless sensors to the upper tier and for the passing of commands from the upper tier down to the wireless sensor network. The server consists of a low-power single board computer (SBC) that operates Linux (Ubuntu 10.04.1 LTS). The SBC is an industrial platform that can safely operate in harsh field conditions including temperature ranging from -40 to 80 C°. A 3G cellular modem is included in the server for the communication of data to and from the server. To power the SBC, a bridge outlet is used with a battery backup solution.

2.2 Upper Tier: Internet-Enabled Cyber-environment

The cyber-environment provided by the upper tier of the monitoring system architecture is responsible for the management of bridge response data. It consists of a high-speed network that provides system end-users with secure access to data. The most important component of the upper tier is the database server. The remotely accessible object-oriented application interfaces (APIs) implemented on the database server allows clients to transparently access bridge data stored on the server. The employed communication technology ensures the integrity of the transferred data, while hiding the data from public access. The server can handle concurrent calls from multiple clients, and can manage data from multiple sensor networks for bridges at different locations. The aggregated sensor data is stored in a high-speed database optimized for numerical data, while monitoring system metadata (*e.g.*, time, structure, location and type of sensors) is stored in a SQL relational database. The database schema supports the transparent linkage of different pieces of information pertaining to the bridge including the location of the sensor nodes, the location of structural nodes in bridge analysis models, and associated archive media files (*e.g.*, inspection reports, bridge photos). This unified management of bridge sensor data and historical inspection efforts provides bridge owners with holistic information on the current structural status of bridges. The internet-enabled distributed server-client applications also permit remote users to conduct the maintenance and reconfiguration of the sensor network system deployed at bridge sites.

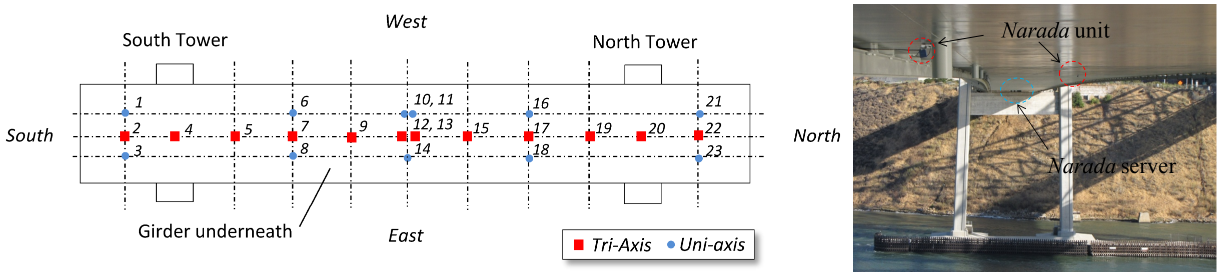


Figure 2. (Left) Initial deployment underneath the main bridge girder; (right) picture of deployed sensors.

3. LONG-TERM DEPLOYMENT AT THE NEW CARQUINEZ BRIDGE

The long-term assessment study of the autonomous wireless monitoring system has been ongoing at the New Carquinez Bridge (NCB) since 2010. The NCB is located over the Carquinez Strait in Vallejo, CA carrying westbound I-80 traffic. The bridge is a long-span suspension bridge with total length of 1056m; the main span is 728m (Figure 2). The bridge consists of an orthotropic steel girder span and two hollow concrete towers. A preliminary performance test of the *Narada* wireless sensors was conducted at several locations in the bridge to identify the best location to install the wireless sensor network for a long-term deployment [6]. Due to the open geometry of the bridge, the wireless communication environment was found to be very stable at most locations except inside the steel girder where large steel diaphragms impede the propagation of wireless signals. The ambient vibration of the main deck was successfully acquired with a short-term network of *Narada* wireless sensors installed on the western side of the main deck. The high quality acceleration response data collected by the *Narada* wireless sensors was validated when performing an accurate system identification of the NCB using the collected data [6]. The extracted modal shapes of the main deck matched those estimated by a high-fidelity finite element model of the NCB implemented in ADINA. In addition, the accuracy of the wirelessly obtained acceleration data was verified through a careful comparison with accelerations measured by tethered force balanced accelerometers permanently installed in the NCB by the California Strong Motion Instrumentation Program (CSMIP); the comparison revealed a nearly perfect match between response data collected at identical measurement points [5].

The primary concern of the California Department of Transportation (Caltrans) was the location of the wireless sensors. With a pedestrian walkway on the western side of the main deck, Caltrans requested sensors not be placed in close proximity to the walkway to ensure the instrumentation does not attract the attention of bridge pedestrians. As a result, the underside of the main girder was selected as the best location for a permanent installation of the *Narada* sensor network. For the long-term deployment, the *Narada* wireless sensor nodes encased in weather-proof containers are mounted to the steel deck using rare-earth magnets to prevent damage to the surface of the steel deck which is coated with an expensive anti-corrosion paint.

3.1 Performance Evaluation through Initial System Deployment

The first stage of installation of the permanent *Narada* sensor network took place in early 2010. All wireless sensors were installed underneath the main deck using a movable scaffolding system. Figure 3(a) shows the plan for the sensor configuration. The initial deployment included an array of 13 *Narada* nodes (*i.e.*, nodes 1 through 10, 12, 14, and 15 in the deployment plan) was installed in the southern half of the bridge girder. A total of 24 sensing channels were used to record the vertical deck acceleration using 6 uni-axial accelerometers and 7 tri-axial accelerometers. The bridge response was collected for two-days. Later, the sensor network was expanded to the northern half of the bridge. An additional 10 *Narada* nodes (*i.e.*, nodes 11, 13, 16 through 23) were installed with 23 channels. The responses of the bridge towers were simultaneously measured using two *Narada* nodes installed on the top of each tower; tri-axial accelerometers were interfaced to each of these nodes. To collect bridge response data, two *Narada* servers were installed; one server was installed in each tower to record data from half of the wireless sensor network. This deployment was intended: 1) to assess the reliability of the wireless communication channel; 2) to evaluate the durability of the *Narada* packaging; 3) to check the capability of synchronizing data acquired using two overlapping sensor network serviced by the south and north tower *Narada* servers.

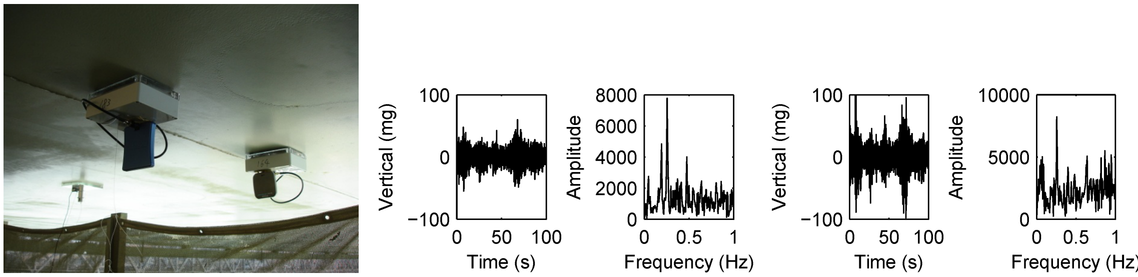


Figure 3. Local plate vibration; deployment view (left); data at the diaphragm (center); data off the diaphragm (right)

The antenna used to communicate data in the wireless sensor network was found to strongly influence the reliability of the communication channel. When both *Narada* nodes and the *Narada* server each utilized a 7 dBi uni-directional high-gain antenna, the server was unable to make a reliable communication with the nodes. The communication performance was significantly improved by replacing the uni-directional antenna at the *Narada* server with a high-gain omni directional antenna. With the omni-directional antenna, reliable line-of-sight communication was easily established between the *Narada* server and most of the *Narada* nodes except for a small number of nodes hidden behind concrete drainage pipes protruding from the main girder. For those nodes behind the drainage pipes, a short extension cable was used to allow the uni-directional antenna to be placed away from the packaged node. The extension cable was limited in length to minimize the attenuation of the wireless signal strength. With the installed monitoring system, the wireless communications were reliable with a 95% success rate in data delivery.

The *Narada* nodes were packaged in weather-proof containers with 6 round rare earth magnets (20 lb magnetic force each) mounted to the bottom of the packaging. The bridge owner (Caltrans) would not allow any sensor to be screwed or epoxy attached directly to the surface of the steel girder due to the anti-corrosion surface coating on the steel deck. The magnetic force was strong enough to carry the weight of the node (*i.e.*, 3 lbs) but the epoxy bond between the container and the magnet proved to be a weakness of the system design. As a result, epoxy glue was later replaced with a screw-type connection between the *Narada* package and the rare earth magnets.

The two *Narada* servers implemented at the towers successfully collected data from the network of *Narada* sensor nodes using two channels in the IEEE 802.15.4 wireless communication protocol. During the deployment, the two servers initiated the data collection using a fixed schedule. The acceleration response data from the two sensor networks were time-synchronized off-line using the data collected by the sensors collocated at the mid-span (*i.e.*, node 10 and 11). The observed time lag between the initiations of data collection by the two servers was found to be usually less than 100 ms but at worst 500 ms. To tighten the synchronization between the two servers, a more robust network time synchronization protocol was used to reduce this error to less than 5 ms.

The acceleration time histories obtained underneath the main bridge girder were found to be sensitive to the specific placement of the accelerometers. Figure 3 shows two sensors mounted only 50 cm away from each other; one sensor was situated in line with a bridge suspender while the other was 50 cm away from the suspender. Placement of the sensor with respect to the suspender is important due to the steel diaphragm located at the suspender; the diaphragm is intended to allow for the complete transfer of the deck dead and live loads to the main suspension cables. As a result, the accelerations measured at this location represent the global dynamics of the bridge. If an accelerometer is placed away from the diaphragm, then local high frequency vibration will be superimposed on the measured accelerations. Figure 3 clearly shows the time history acceleration response, accompanied by the corresponding response spectra, collected from the 2 *Narada* wireless sensors. The flexibility of the girder bottom plate away from the diaphragm clearly amplified the measured acceleration. This resulted in an elevated level of noise in the response spectra making modal peak detection challenging for high order global modes. This observation suggested that *Narada* units should be installed in line with the main suspenders in order to capture the global bridge dynamics.

3.2 Long-Term System Deployment with Internet-Enabled Cyber-environment

Due to the observations made during the initial system deployment, the system was reconfigured and updated during the time period of October 2010 and January 2011. The dense array of tri-axial accelerometers were installed underneath the bridge girder (denoted as nodes 1 through 19 in Figure 4) while environment sensors (*e.g.*, thermometer, anemometer, and wind vane) were installed on the main deck (denoted as nodes 20 and 21). The *Narada* hardened container was updated to protect the electronics from moisture. Figure 5 shows the *Narada* node fully assembled prior to mounting on the bridge girder. In addition, the figure shows the installation of the wind speed and wind direction sensors on the main deck in the center of the bridge. After the *Narada* nodes were installed, they were connected to the solar panels placed on the top side of the main span via shielded wiring. The solar panels were installed with a steep angle so that a sufficient level of energy is harvested during the winter when the altitude of the sun is low.

The *Narada* servers installed at the towers underneath the girder each cover half of the bridge (Figure 5): the server installed at the south tower commanded nodes 1 through 10 and 20 while the server at the north tower commands nodes 11 through 19 and 21. The servers allowed the upper tier of the cyber-environment to initiate timed data collection via a 3G cellular connection via an SSH connection. The upper tier of the monitoring system architecture was also responsible for ensuring the two *Narada* servers were synchronized using the network time protocol (*e.g.*, NTP).

The *Narada* sensor network was commanded to collect data every 4 hours with a sampling rate of 20 Hz for 500 seconds (Figure 6). Underneath the girder, the maximum acceleration amplitudes in the transverse and vertical directions of the bridge were in the ranges of 10 to 20 mg and 100 to 200 mg, respectively. The clear peaks in the Fourier response spectra of the acceleration data indicated the vibration modes of the main deck could be identified. The climate sensors mounted to the suspension cable in the center of the main span provided valuable environment data of the bridge

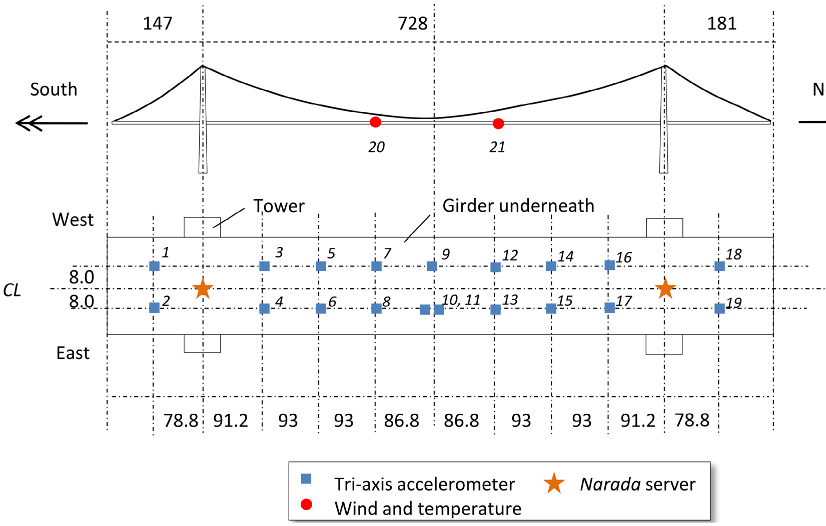
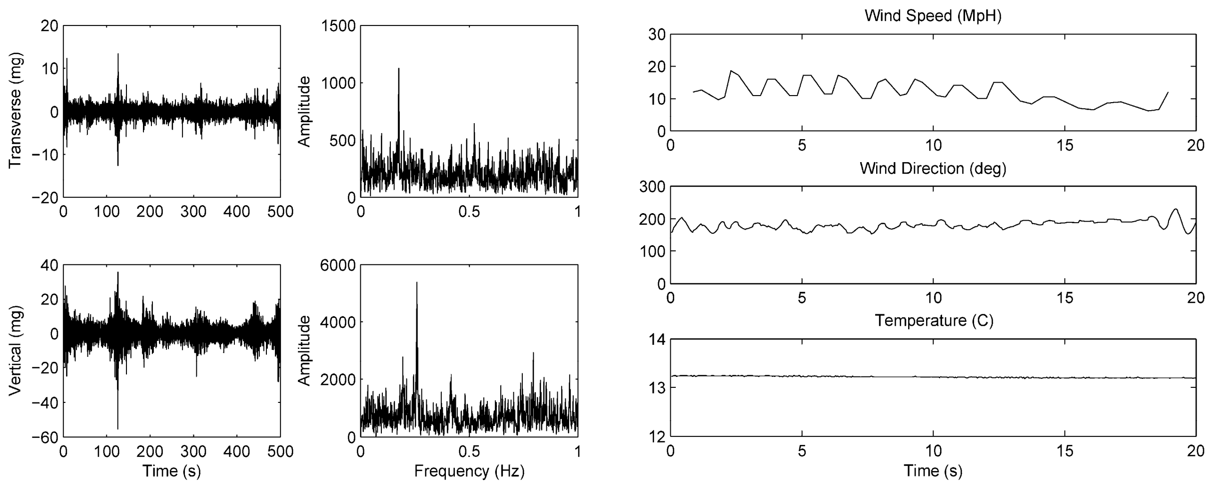


Figure 4. Long-term sensor deployment plan

Figure 5. Wireless monitoring system components: (left) *Narada* assembly with solar energy harvester; (middle) climate sensors installed on the main deck; (right top) solar panel on the main deck; (right bottom) server at tower location.



(a) Acceleration time history and associated response spectrum (b) Climate sensor data

Figure 6. Sample sensor data obtained from the NCB wireless monitoring system (January 2011).

including wind speed, wind direction and temperature. The two-tiered wireless monitoring system has continued to operate to the date of this publication. The database server in the upper tier logs the data collected as well as any errors encountered during operation. In addition, the wireless sensors communicate the voltage of their battery packs which is tracked by the database server.

4. GLOBAL BRIDGE DYNAMICS

4.1 Modal Property Estimates

The long-term deployment of the *Narada* sensor network has provided a large data set spanning many months with varying environmental conditions. One usage of the collected data sets is the extraction of modal properties of the bridge (*i.e.*, system identification). The information obtained through system identification analyses using the bridge acceleration data provides a quantitative basis to: 1) validate sensor performance; 2) evaluate the environmental effects on the bridge dynamic features; 3) validate and update high-fidelity finite element (FE) model. The main input loads for the ambient vibration of the bridge are traffic and wind loads. Without an accurate measure of these transient loads, output-only system identification techniques (*e.g.*, complex mode identification function (CMIF), frequency domain decomposition (FDD), stochastic subspace identification (SSI)) are widely used by the civil engineering community. An overview on the performance of the available output-only system identification techniques has been reported by several researchers [6, 7]. Here, the FDD technique was applied for system identification because of its simple formulation and inexpensive computational effort. Figure 7 shows the modal properties of the main deck in the vertical vibration direction using an acceleration data set collected on January 26, 2011. Clear peaks appeared in the singular values plots of the power spectral density (PSD) functions; this indicated the modal frequencies to be 0.192 Hz, 0.259 Hz, 0.351 Hz, and so on. The first several modal shapes of the main deck are schematically plotted in Figure 7. The 1st, 2nd and 5th modes have nice symmetric mode shapes while the 3rd, 4th and 6th modes are somewhat distorted. Several reports publish the modal properties of the NCB as extracted from data collected before the bridge opened and using response data collected from the CSMIP sensors installed inside girder [8, 9]. The modes obtained from the *Narada* sensor network correlate well to those previously reported. The global vibration characteristics of bridges are known to vary under different atmospheric conditions (*e.g.*, temperature and wind condition). Hence, an extensive database of long-term bridge behavior is desirable to statistically assess the effects of environmental parameters on the vibration characteristics of the bridge [10, 11].

4.2 FE Model Comparison

The experimentally extracted modal properties correspond to the real condition of the bridge at the time of data collection. Modal data is widely used to update finite element models of the instrumented structure to capture the conditions of the structure (*e.g.*, material properties, bearing condition, damage condition, *etc.*). The finite element (FE)

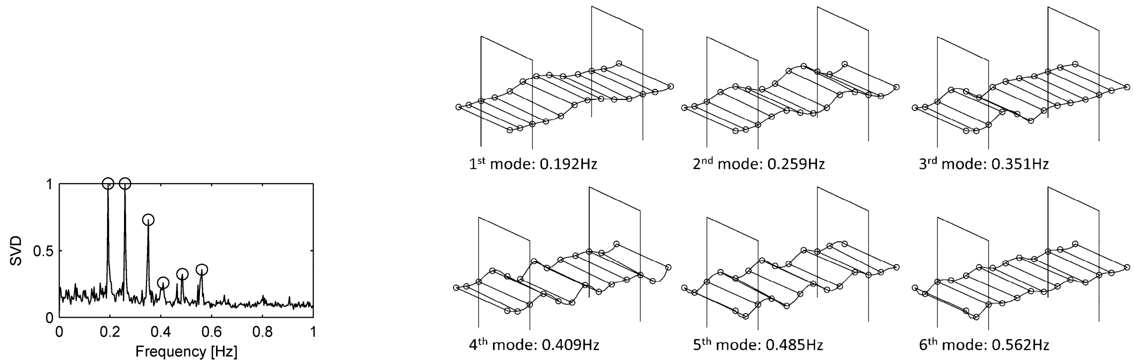
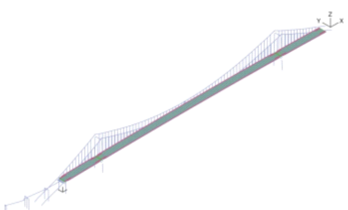
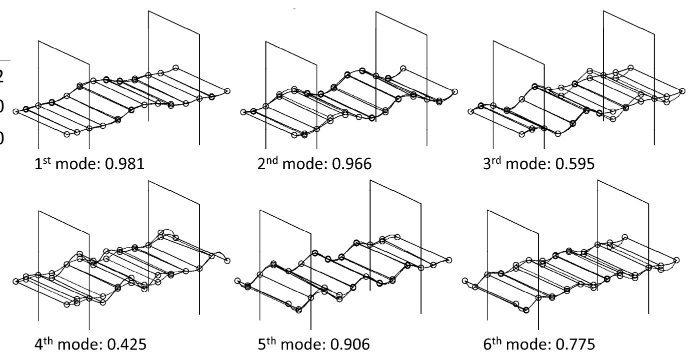


Figure 7. (Left) modal frequencies identified by singular value plot; (right) first 6 mode shapes in the vertical direction.

Table 1. Modal frequency estimates.

	1st	2nd	3rd	4th	5th	6th
Test (Hz)	0.192	0.259	0.351	0.409	0.485	0.562
FEM (Hz)	0.212	0.271	0.365	0.411	0.495	0.580
Diff. (%)	10.4	4.63	3.99	0.489	2.06	3.10





(a) FE model of the NCB

(b) first 6 mode shapes with corresponding MAC values

Figure 8. Modal property comparison: *Narada* sensor data and finite element model.

model of the NCB has been modeled using as-built drawings provided by Caltrans (Figure 8(a)). Specifically, the FE model has been created to capture the construction sequence so that residual stresses in key bridge elements are accurately captured. However, the soil properties of the bridge foundation and stiffness reductions due to cracking in the concrete towers are not accounted for in the current model. The FE model was created using ADINA, a commercial finite element package widely used in the civil engineering community. The mesh size of the ADINA model of the NCB has 155,619 degrees of freedom with 159 truss elements, 14 spring elements and 19446 isotropic and orthotropic shell elements.

The modal properties estimated by the FE model were compared with those extracted from the sensor data at the NCB. The FE model estimated modal frequencies close, but slightly higher than those extracted experimentally. This may be attributed to the boundary condition of the FE model where soil properties around the foundations are neglected. The mode shapes extracted from the test data and those from the FE model matched well especially in 1st, 2nd and 5th modes with modal assurance criteria (MAC) values higher than 0.9 (Figure 8(b)). The experimental mode shapes of the 3rd and 4th modes looked slightly distorted. In both modes, only the half of the main deck seems to be excited in the experimental results. A reduced order model of the high-fidelity FE model has been constructed and is being continuously updated using the archive collection of bridge modal properties extracted from the sensor data.

5. SUMMARY

A dense network of low-power wireless sensors has been deployed on the New Carquinez Bridge. An array of *Narada* wireless sensor nodes has been installed on the main girder to continuously monitor the bridge vibration response and climate condition; the system has been operating since January 2011. The collected data is autonomously transferred to a remote database via a 3G cellular network and stored securely with regularly scheduled backups. The backbone of the constructed autonomous wireless monitoring system is the cyber-environment specifically developed for this project.

The hierarchical design of the bridge monitoring system allows for secure two-way communication between the upper and lower tiers (*i.e.,* between the central database server and the client data collection servers at the bridge site). The bridge vibration responses obtained through the deployed sensor network has been used for: 1) validation of the long-term sensor performance; 2) assessment of the cyber-environment performance; 3) system identification of the bridge; 4) calibration and model updating of the high-fidelity and reduced-order FE models. By populating the database with bridge response data over long periods of time, the impact of changes in atmospheric conditions on the bridge vibration characteristics can be determined. Other ongoing efforts include the remote testing of the embedded sensor algorithms for in-network interrogation and senor failure identification, and the development of data mining and decision making tools for translating sensor data into meaning information for bridge owners.

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