

Performance Testing of Wireless Intelligent Sensor and Actuator Network (WISAN) on a Pre-Stressed Concrete Bridge

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Abstract: - With advances in sensor technology and availability of low cost integrated circuits, a wireless monitoring sensor network has been considered to be the new generation technology for structural health monitoring. Wireless Intelligent Sensor and Actuator Network (WISAN) has hence been developed as a vibration based structural monitoring network that allows extraction of mode shapes from output-only vibration data from a structure. The mode shape information can further be used in modal methods of damage detection. This network has been tested on a pre-stressed concrete bridge in Kuala Lumpur, Malaysia. The results have been compared with a similar sized steel girder bridge.

Key-Words: - wireless, intelligent sensor, actuator network, bridge monitoring, damage detection

1 Introduction

Structural Health Monitoring (SHM) has received increasing research interest in the recent years. Studies have shown that the economic losses associated with disasters are much higher as compared to cost for continuously monitoring the structure's health and performing early repairs avoiding major calamities [1]. Among the different available damage detection techniques, the class of vibration-based damage detection techniques is one of the most popularly used methods to monitor the condition of structures. A damage detection process usually involves comparing specific properties of both damaged and undamaged mode shapes and determining locations where the difference in properties is above a specific threshold [2]. However, the first step for detection of damages from any structures is successfully obtaining the mode shape of the structure. A monitoring system using time-synchronized sensors placed at various locations on the structure is needed to acquire vibration response. A wireless sensor network is a potential candidate for this task due its low cost hardware, ease of installation and use. The task of vibration acquisition poses additional requirements for the sensor network, specifically, time-synchronized acquisition among sensors; lossless and preferably real-time data transmission; scalability to various structure sizes. Wireless Intelligent Sensor and Actuator Network (WISAN) has been, developed to address these issues and support massive arrays of heterogeneous sensors with constant data streams that

can be used as a reliable monitoring network. This network has been used to successfully identify natural frequencies and reconstruct partial mode shapes from a pre-cast pre-stressed concrete bridge.

2 Wireless Intelligent Sensor and Actuator Network

WISAN has been developed as a reliable tool for vibration based monitoring of structures. The devices in the network are built around the ultra-low power MSP430 microcontroller MSP430F1611 from Texas Instruments [3] and radio transceiver from Chipcon [4]. WISAN is fully compatible with IEEE 802.15.4 and can be utilized worldwide in 2.4 GHz ISM frequency band and coexist with Wi-Fi and other devices. The microcontroller and radio form the major part of the on-chip components on the sensor. Peripheral circuitry provides interface with sensing elements (accelerometers, strain gauges, etc.), display panels (LCDs), storage cards, USB interface etc. The network hardware is built using two types of devices:

- (a) The PAN Coordinator and,
- (b) The Wireless Sensor.

The PAN Coordinator (Figure 1) is responsible to maintain a cluster of sensor nodes, send commands, receive data and store, process and/or send data to a personal computer. The PAN Coordinator can be interfaced to a personal computer via a serial link over the USB. A terminal pin connector provides direct input

of the Pulse-per-Second (PPS) hardware signal from a GPS receiver, enabling highly precise synchronization of the globally networked devices. The wireless sensors (Figure 2) are used for sampling data via different sensing elements and sending them to the PAN Coordinators. The peripheral circuitry used to interface sensing and actuating elements to the wireless sensors consists of a variety of components that may be selected as the application desired. A low power 3D MEMS accelerometer (LIS Accelerometer, [5]) is used as internal on-board sensor. An optional gain and offset compensation stage is provided to improve the resolution. Signal conditioning is done using a 5th order low-pass filter with software configurable cutoff frequency. The noise resolution of the accelerometer in the frequency band of 100Hz is 0.5 mg. An optional buffered output terminal allows sourcing of control and excitation signals that can be used as actuation signals. A connector is provided for interfacing external acceleration sensor. A differential signal conditioning circuitry is also provided with a gain of 1000 to interface high precision strain sensors. The wireless sensors are enclosed using commercially available NEMA4 enclosures. All circuits feature shutdown inputs, so a part or the whole node may be put into low-power sleep mode.

WISAN software has been developed to efficiently work with low power hardware and satisfy all the stringent requirements of a continuously monitoring wireless sensor network. The network protocol is the key ingredient of any networked system, since it is responsible for reliable, error-free and on time data delivery. The medium access protocol network software is based on the low-latency, low-power IEEE 802.15.4 protocol which has emerged as a new standard for low rate wireless personal area networks (LR-PANs) [6] and hence chosen for WISAN. Since the IEEE 802.15.4 protocol only provides the lower layers, that is, the Physical layer and the Medium Access Layer, the software development for the network also focused on developing application and transport layers of the network. Bandwidth optimization using reservation based scheduling has been implemented in WISAN [7]. WISAN network topology used for monitoring the health of structures is shown in Figure 3. Wireless sensors remain static on the structure and organized into a hierarchical cluster tree based architecture where most of the communications between sensor nodes and dedicated cluster heads is performed in single hop. A certain number of sensors (within the maximal allotted bandwidth) are associated with a particular receiver using a unique PAN Identifier. The PAN Coordinators scan and select one of the 16 frequency channels from the 2.4 GHz

frequency band. A synchronization signal is provided using GPS and an uplink connection provided to a personal computer. Each cluster can be spread to a maximal range of about 100 feet and a maximal of 16 clusters can be used in a given area which can be organized in a hierarchical structure to cover large structures. Time synchronization algorithm is implemented at the sensor nodes to synchronize sensors within a single cluster (using periodic beacons from the PAN Coordinator) and in the PAN coordinator to synchronize individual clusters (using PPS from GPS). These algorithms synchronize any two sensors in the network to the order of $\pm 23\mu s$. A TCP based server and LabView based client has been developed to control these different clusters using a single application software. Thus, large structures can be monitored at the cost using the reliable, low power, time synchronous and scalable hierarchical network WISAN.



Figure 1: WISAN PAN coordinator



Figure 2: WISAN sensor node

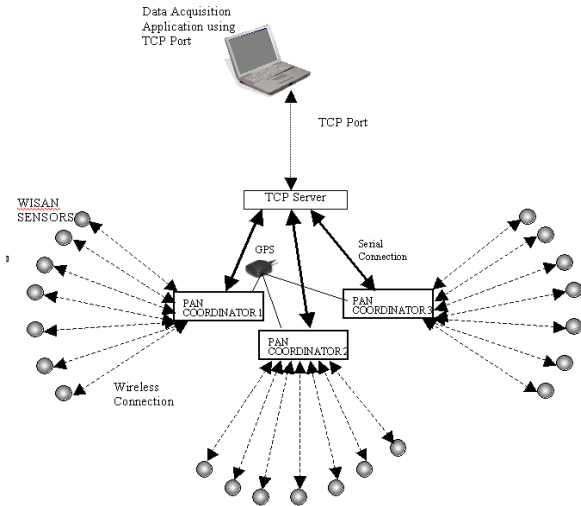


Figure 3: Layout of the hierarchical cluster based wireless sensor network for monitoring the structural health of bridges.

was sampled at the rate of 240.385 Hz and a data resolution of 14 bits. The cut-off frequency of the programmable filter was set to 100 Hz. Vehicular traffic over the bridge was the source of excitation. Acceleration data from the sensors were recorded for time intervals of 2 minutes, 5 minutes and 10 minutes. The data collected from all the sensors was processed using the output-output modal analysis software ARTeMIS [8].



4(a)



4(b)

Figure 4 (a): Photo of the bridge on Route 1 and (b) Details of the bridge from the test site

3 Mode Shape Extraction from a Concrete Bridge

WISAN was originally designed to monitor structures built using steel girder technology. However, the same principles could be applied to modal testing of pre-stressed concrete structures. The presented experiment had the goal of demonstrating that reconstruction of mode shapes of a pre-stressed concrete bridge is possible from the data captured by a time-synchronized sensor network. The bridge on Route 1 at Kuala Lumpur, Malaysia was chosen as the test location (Figure 4). The bridge is built using 22 pre-stressed concrete girders with integral abutment. Total length of the bridge is 18m, width is 22m. The highest point is 5m above ground level with easy access to girders available in area of about 3m from both supports (Figure 5). Due to accessibility limitations the network was setup by attaching 22 sensors to 11 middle girders at a distance of 2.8m from both supports as shown in Figure 6. Thus, the dimension of the part of the structure that was tested is 18m x 10m. The sensors were clamped to the side of an aluminum plate glued to the girder as shown in Figure 7. The PAN Coordinator station is placed under the bridge on the bottom left of the entire setup. The PAN Coordinator station consisted of 3 PAN Coordinators connected to a laptop via serial interface. GPS was used to provide pulse per second synchronization signal to the PAN Coordinators. The network configuration for the test is as shown in Figure 3. The sensors formed three network clusters on three independent frequency channels. Acceleration data



Figure 5: View from under the bridge

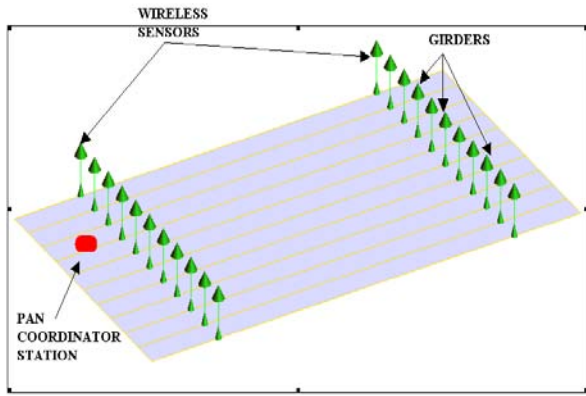


Figure 6: Layout of the bridge test setup for the four girder grid setup



7(a)



7(b)

Figure 7: View of (a) single sensor and (b) 11 sensors attached to the girders

4 Results and Discussion

The acceleration response from each sensor location was processed using ARTeMIS and peaks were identified corresponding to the modal frequencies. Table 1 and Table 2 summarize modal frequencies along the length and width of the bridge respectively. It may be noted that since there were only two sensors on each girder along the length, lesser number of modal frequencies are

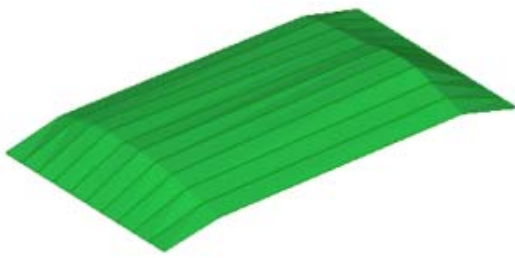
identified. Corresponding bending mode shapes have been plotted in Figure 8 – Figure 9 by using the relative sensor amplitude at a particular mode frequency. Acceleration data from a sensor located on the second girder (Figure 10) suggests a peak amplitude in the frequency spectrum of around 28 mg in the range of 8 – 12 Hz. Assuming this corresponds to the amplitude of the first bending mode observed at 10.74 Hz, the maximum displacement at the center (interpolating the data) would be around 50mg. With the sensor noise resolution of 0.5mg, the peak data resolution possible is around 7 bits out of 12 bits possible. It is interesting to compare the results obtained from the concrete structure to those of a similarly-sized steel girder structure. In our previous work [9], we used WISAN to extract mode shapes from a RT31 steel bridge located in the Town of Lisbon, New York. This bridge has four steel girders (3m apart) and overall dimensions 19m x 10m. The bridge was equipped with 44 sensors, 11 sensors spaced equidistantly on each girder. Comparison between the concrete and steel structures shows that both bridges have comparable modal frequencies predominantly in the range of 10Hz-30Hz (Table 3). However, there is a significant difference in the maximal amplitude attained by the structural components. Testing of the concrete RT1 bridge in Kuala Lumpur was conducted under constant heavy traffic including heavy vehicles. The maximal amplitude of vibration at a distance of 2.8m from supports was 28 mg. Testing of the RT31 steel girder bridge in New York was under intermittent traffic with the most of one light vehicle on the bridge at a time. The maximal amplitude of vibration at a distance of 2.845m from supports was 24 mg. As these results show, a steel bridge achieved comparable levels of excitation under a much lighter traffic. Practically this means that vibration sensors with lower noise floor are necessary for monitoring of pre-stressed concrete structures since vibration levels may be lower than those of steel girder bridges.

Table 1: Vibration modal frequencies along the length of the bridge

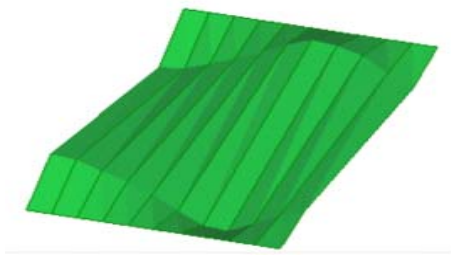
S.No.	Frequency (Hz)	Nature of Mode Shape
1	10.74	Bending mode with single curvature
2	32.1	Coupled bending and torsional mode

Table 2: Vibration modal frequencies along the width of the bridge

S.No.	Frequency (Hz)	Nature of Mode Shape
1	15.43	Torsional Mode
2	18.49	Bending mode with single curvature (first mode)
3	23.18	Second bending mode
4	29.05	Third bending mode

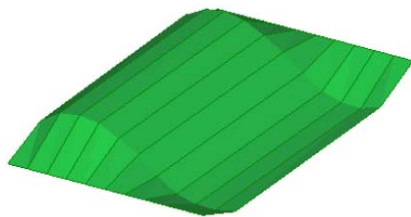


8(a)

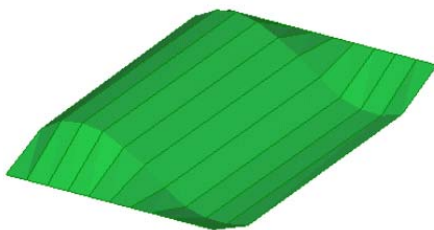


8(b)

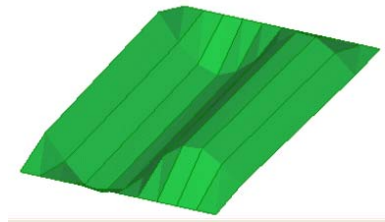
Figure 8: Mode shapes along the length of the bridge at frequencies (a) 10.74 Hz and (b) 32.1 Hz



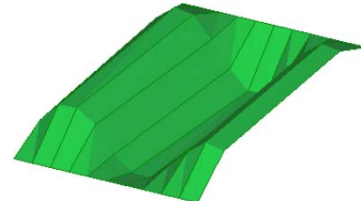
9(a)



9(b)

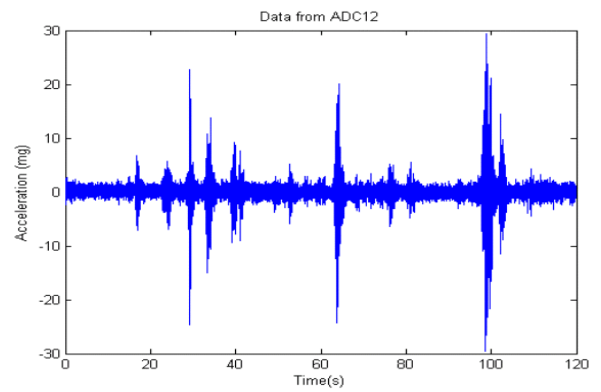


9(c)

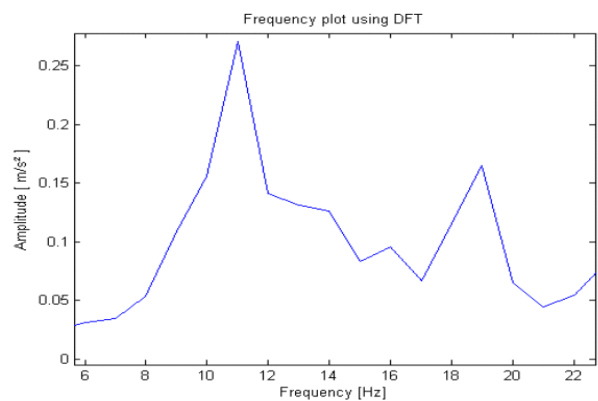


9(d)

Figure 9: Mode shapes along the width of the bridge at frequencies (a) 15.43Hz (b) 18.49 Hz (c) 23.18 and (d) 29.05 Hz



10(a)



10(b)

Figure 10: (a) Acceleration data from sensor located on the second girder. (b) Frequency spectrum of data from sensor located on the second girder

Table 3: Comparison of natural frequencies on steel and concrete girder bridges

S. No.	Mode Frequency on Concrete Bridge (Hz)	Mode Frequency on Steel Bridge (Hz)	Nature of Mode Shape
1	10.74	9.155	Bending mode with single curvature along the length
2	23.18	26.23	Second bending mode along the width
3	32.1	32.75	Coupled bending and torsional mode along the length

provided by Structural Vibration Solutions A/S, at <http://www.svibs.com/>

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5 Conclusion and Remarks

Mode shape extraction from ambient vibrations on a structure is the first step towards vibration based damage detection using monitoring sensor networks. WISAN is a sensor network that has been specifically developed for monitoring applications. This network has been demonstrated to identify natural frequencies and reconstruct mode shapes from a pre-cast pre-stressed concrete bridge. Obtained frequencies and mode shapes were similar to those obtained from a similar sized steel girder bridge of comparable excitation levels. The concrete bridge under test recorded very with low excitation levels (28 mg at 2.8m from the supports) giving only 7 bits of sensor resolution. Hence, sensors with lower noise floor may be needed for modal damage detection. Overall, the test shows successful extraction of mode shapes from very low ambient vibrations on a bridge which is the first step towards damage detection from structures.

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