TECHNOLOGY

information and updates on the impact of technology on structural engineering

Figure 1: Twin Jindo Bridges (2nd Jindo Bridge is on the left).

Wireless Monitoring of Civil Infrastructure Comes of Age

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Medical personnel routinely perform health screenings for the early detection of disease so that appropriate preventive measures can be taken. Health is an important issue not only for our population but also for our nation's civil infrastructure, much of which is rapidly approaching the end of its intended design life. With age comes deterioration; the most recent evaluation by the American Society of Civil Engineers cites grimly poor "grades" for almost all infrastructure types. The need for routine monitoring of civil infrastructure is now more critical than ever.

Bridges account for a large part of the capital investment in the construction of road networks and represent a key element in terms of the safety and functionality of the entire highway system. Structural health monitoring (SHM) offers the ability to continuously observe the integrity of our nation's bridges in real time, with the goal of enhanced safety and reliability, and reduced maintenance and inspection costs. Furthermore, such SHM systems allow for emergency facilities and evacuation routes, including bridges and highways, to be assessed for safety after catastrophic events, such as earthquakes, hurricanes, tornados, etc.

Many recently constructed bridges have in-depth, yet costly, monitoring systems. For example, the total cost of the monitoring system on the Bill Emerson Memorial Bridge in Cape Girardeau, Missouri, is approximately $1.3 million for 86 accelerometers, which makes the average installed cost per sensor a little more than $15,000; this cost is not atypical of today's wired SHM systems.

This article discusses a low-cost, wireless means for continuous and reliable structural health monitoring recently developed by researchers at the University of Illinois at Urbana-Champaign, as well as its successful deployment at full scale on the 2nd Jindo Bridge in South Korea (*Figure 1*). This SHM system is the first long-term, dense deployment of a wireless sensor network to monitor civil infrastructure and demonstrates the tremendous potential of this technology.

Next Generation Wireless Smart Monitoring System

While much of the technology associated with wireless smart sensors (WSS) has been available for over a decade, only a limited number of full-scale implementations have been realized, primarily due to the lack of critical hardware and software elements. Using MEMSIC's Imote2, researchers at the University of Illinois at Urbana-Champaign have developed a flexible WSS framework for full-scale, autonomous SHM that integrates the necessary software and hardware elements, while addressing key implementation requirements. The hardware delivers the necessary high-fidelity data, while the software allows

Figure 2: Imote2/ISM400 wireless smart sensor node.

Figure 3: Sensor layout on the Jindo Bridge.

engineers to more readily realize the potential of smart sensor technology.

An example of one such critical issue addressed by this framework is network scalability. A wireless sensor network implemented on the Golden Gate Bridge in 2008 took approximately 10 hours to collect 80 seconds of data (sampled at 1000 Hz) from 56 sensor nodes to a central location. To address such problems, Illinois researchers leverage the on-board computational capacity of the WSSN to allow data processing to occur within the network, as opposed to processing at a central location. By implementing data processing techniques (e.g., modal analysis or damage detection algorithms) in such a distributed manner, the amount of communication that occurs within the network can be reduced, while still providing usable information on the structural condition. The Illinois WSS framework provides a cost-effective and scalable solution that is revolutionizing structural health monitoring.

Wireless Smart Monitoring System on the Jindo Bridge

A joint effort between the University of Illinois at Urbana-Champaign, KAIST and Seoul National University in Korea, and the University of Tokyo in Japan was undertaken in 2009 to demonstrate the efficacy of this wireless smart sensor framework, resulting in the first autonomous, full-scale implementation of a wireless smart sensor network for structural health monitoring on the Jindo Bridge in South Korea.

Opening in 1984, the 1st Jindo Bridge is a cable-stayed bridge connecting the Korean peninsula and the Jindo Island; however, growing traffic demands quickly exceeded the load carrying capacity of the first bridge. The 2nd Jindo Bridge, which opened in 2005, is a streamlined steel box girder with a center span of 344 meters (1129 feet) supported by 60 parallel wire strand cables anchored to two diamond-shaped pylons.
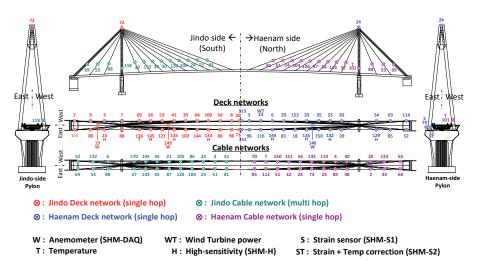
The wireless monitoring system on the 2nd Jindo Bridge was initially installed in the summer of 2009. Seventy-one state-of-the-art wireless smart sensor nodes, with a total of 427 sensing channels, were installed on the girder, the pylons, and the cables. Each node was comprised of the Imote2 (including on-board CPU, radio, power management integrated circuit), the ISM400 sensor board, and a battery (*Figure 2*). Measurements included 3-axes acceleration, plus temperature, humidity, and light. Combined with the ISHMP Services Toolsuite, these powerful nodes allow for synchronized data collection, aggregation, synthesis, and decision-making in real time.

The smart sensor nodes for the deck, pylons and cables were attached using different methods. The nodes were mounted to the steel deck and pylons using two magnets, each with a holding capacity of 10 kg, attached to the bottom of the enclosure. The nodes were mounted to the cables using two U-bolts and an aluminum mounting plate. These methods of mounting the sensors have proven to be fast, inexpensive, and secure.

Based on the success of the 2009 deployment, the monitoring system was extended in 2010 to include 113 WSS nodes, measuring a total of 659 channels of data, (*Figures 3 and 4*), resulting in the world's largest wireless smart sensor network for SHM. The ISM400 sensor board is used on 100 nodes. A new high-sensitivity accelerometer board (SHM-H board) developed by the Illinois research team, which enables measurement of accelerations as low as 0.05 mg, is used for 10 nodes. The remaining three nodes are connected to 3D ultrasonic anemometers to measure and collect, wirelessly, the speed and direction of the wind on the bridge.

Figure 4: Example of wireless smart sensor nodes deployed on the Jindo Bridge.

This year, a wireless strain measurement became available with the newly developed SHM-S sensor board. All 113 nodes are self-powered using solar or wind harvesting. The sensors use both single-hop and multi-hop communication protocols to interact with two base-station computers, which are remotely accessible via the Internet. Should any anomalies in the measured data be detected during the autonomous system operation, the base-station computers automatically email the research team so that appropriate action can be taken.

The monitoring system can autonomously estimate various physical states of the bridge. For example, the modal properties (i.e., natural frequencies, modal damping, and mode shapes) can be obtained from the measured accelerations and utilized to refine the numerical model, to determine structural performance, and to find locations of possible fatigue damage. Cable tension force, one of the most important integrity measures for cable-stayed bridges, is estimated automatically using a vibration-based method. Deck-cable interaction, which may cause dynamic instability, also can be assessed. Aerodynamic and aeroelastic properties of bridges are estimated based on the synchronized wind speed and response data. This dense information enables comprehensive monitoring of the bridge's health.

Typhoon Kompasu Hits Jindo

In September 2010, Typhoon Kompasu hit the Korean Peninsula with sustained winds of 54 m/s (195 km/h or 121 mph). The Korea Meteorological Administration (KMA) station at Jindo Island measured wind speeds of 15-20 m/s (or 49 to 6 ft/s) out of the SSE (*Figure 5*). The measured wind by the wireless monitoring system was 18-26 m/s from the southeast, slightly faster than reported by KMA station and likely due to the local topography.

During Kompasu, the vertical acceleration of the deck exceeded 20 mg, which is greater than the level of acceleration generated by a 40-ton truck (*Figure 6*). Nonetheless, these accelerations were below the limit of 50 mg proposed in the Korean *Design Guidelines of Steel Cable-Supported Bridges*.

The modal properties of the deck and pylons were obtained using the acceleration data. Utilizing an output-only modal analysis approach, nine vertical bending modes and one torsional mode were clearly identified from the vibration induced responses measured during the typhoon (*Figure 7* and *8*). Compared with the identified modes using the data from an existing wired high-precision accelerometer on the bridge, the current SHM system is found to provide highly accurate modal properties.

The wind velocity fluctuations were measured with ultrasonic anemometers installed along the bridge. This collected data enables the estimation of spatial as well as temporal variation of the wind velocity along the bridge. The steady wind load coefficients and flutter derivatives were also obtained from a series of wind tunnel tests using a ⅟₃₆ scaled model of the deck section. The buffeting analyses results considering aerodynamic admittance effects show good agreement to the measured responses (*Figure 9*). This effort offers a significant enhancement in evaluating the aerodynamic safety and serviceability of bridges during strong winds by using synchronized simultaneous measurement of wind and acceleration data along the bridge.

The tensions in the bridge's stay cables were obtained autonomously using vibration data, combined with the known cable properties (i.e., length, weight, stiffness, etc.). In this approach, the vertical acceleration was used primarily to estimate the tension, while longitudinal and lateral accelerations helped to delineate the modes unique to the cable (as opposed to the deck and pylon). Estimated tensions during the typhoon were compared with the design tensions and those obtained in the previous routine inspection. As shown in *Figure 10*, the current cable tensions are close to their design
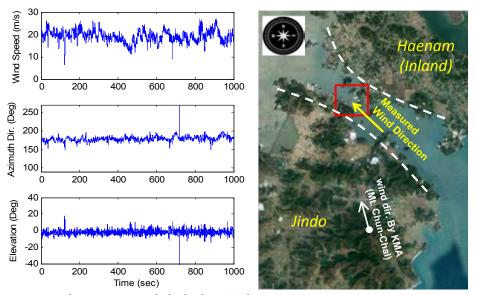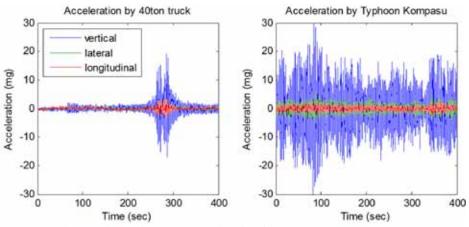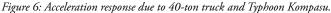

Figure 5: Wind measurements on the bridge during Typhoon Kompasu.

Figure 6: Acceleration response due to 40-ton truck and Typhoon Kompasu.
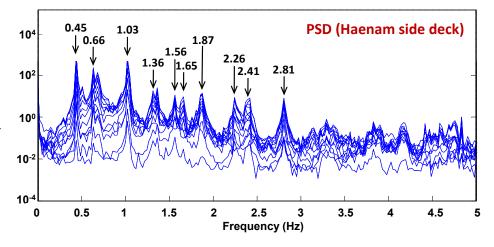

Figure 7: Power spectrum for bridge responses during Typhoon Kompasu.

values and have changed little from the 2008 inspection, which confirms the integrity of the bridge. Thus, continuous monitoring of this important health indicator is facilitated.

In addition to continuously monitoring the bridge structure, the WSS network monitors itself. For example, the battery power system is assessed periodically, including the charging current from the solar panel and the battery voltage (*Figure 11*). Should the battery voltage in a specific node become too low (e.g., due to too many cloudy days), the node is put into a deep sleep until the batteries can be charged and the node brought safely back online.
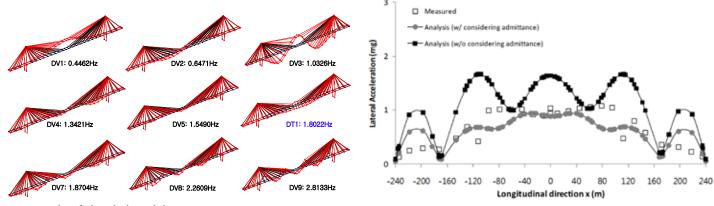
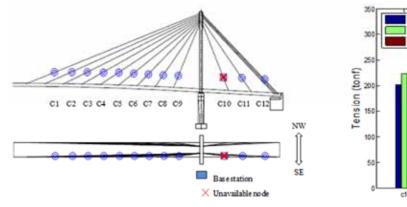Figure 8: Identified mode shapes below 3 Hz.

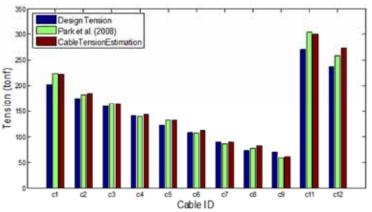Figure 9: RMS acceleration from buffeting analyses and measurement.

Figure 10: Comparison of estimated cable tensions.

Conclusions and Future Work

Smart sensing technology for structural health monitoring is an important field that is coming of age. Combining civil engineering knowledge with developments in sensor technology and network/information management has provided a solution that is a robust and significantly lower-cost (approximately $100 per channel) alternative to traditional wired monitoring systems. Indeed, WSS provides an important new tool to help engineers address the many challenges of managing civil infrastructure. Finally, a joint effort between MEMSIC and the University of Illinois is currently underway to develop the next-generation wireless smart sensing nodes for structural health monitoring.

For more information on the development and implementation of the smart sensor network, visit the ISHMP site at **http://shm.cs.illinois.edu**.▪

Figure 11: Monitored battery voltage and charging current.

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