KSCE Journal of Civil Engineering (2011) 15(1):1-14
DOI 10.1007/s12205-011-0001-y

Structural Engineering
www.springer.com/12205

REVIEW PAPER

Smart Sensing, Monitoring, and Damage Detection for Civil Infrastructures

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Received November 8, 2010/Accepted November 8, 2010

Abstract

In this paper, recent research and application activities on smart sensing, monitoring, and damage detection for civil infrastructures are briefly introduced. Emphasis is given to the activities in Korea. First, the state of the art in smart sensors technology is reviewed including optical fiber sensors, piezoelectric sensors, and wireless sensors. Then, a brief overview is given to the recent advances in the structural monitoring/damage detection techniques such as ambient vibration-based bridge health evaluation, piezoelectric sensors-based local damage detection, wireless sensor networks and energy harvesting, and wireless power transmission by laser/optoelectronic devices. Finally, recent collaborative R&D activities on smart structure technologies in Korea are discussed, which have been carried out on test-road bridges, cable-stayed bridges, and railroad bridges, sharing the up-to-date information and promoting the smart sensors and monitoring technologies for applications to civil infrastructures.

Keywords: *smart sensors, structural health monitoring, damage detection, civil infrastructures*

1. Introduction

The modern civil engineering structures are becoming more complex and are expected to be fully functional under severer environmental conditions. They are often exposed to severe loadings, especially at extreme events such as earthquake and typhoon, which may cause serious concerns on the integrity of the structures, and even collapses that may induce a large number of casualties as well as social and economic problems. Furthermore, the number of deteriorated infrastructure systems in Korea, built in the industrialized period of the 1970s, has increased rapidly. Such problems with the rapid increase of the deteriorated structure are very common all over the world. To cope with the increased demand to monitor structures for safety and serviceability to the community, the Korean governmental authorities issued more stringent requirements on infrastructures management and operational programs. They include systematic visual inspection, instrumentation, load capacity tests, and field measurements for design and construction verification, and long-term performance monitoring and assessment (Yun *et al.*, 2009a).

In this paper, the recent research trends are reviewed for smart Structural Health Monitoring (SHM) on civil infrastructures. SHM is a methodology to examine the structure for possible damage and provide information about any damage that is detected, which offers an opportunity to reduce the cost for the maintenance, repair, and retrofit throughout the life-cycle of the structure. A SHM system typically consists of an onboard network of sensors for data acquisition and some central processors to evaluate the structural health (Hall, 1999; Kessler *et al.*, 2002; Raghavan *et al.*, 2007). This paper focuses on the following three subjects: (1) smart sensors and sensing systems such as optical fiber sensors, piezoelectric sensors, wireless sensors, and vision-based displacement measurement system; (2) smart monitoring and damage assessment techniques including vibration-based SHM systems for determining structural properties and load carrying capacities, electromechanical impedance-based and guided waves-based damage assessments using piezoelectric sensors, wireless sensor networks for effective SHM for large systems, wireless power/data transmission issues, and energy harvesting/saving devices; and (3) recent collaborative R&D activities on smart monitoring technologies including international joint researches on test-road bridges and cable-stayed bridges.

2. Smart Sensors

In this section, recent development and applications of smart sensors and sensing systems are introduced including Optical Fiber Sensors (OFS), piezoelectric sensors, smart wireless sensors, and vision-based displacement measurement systems. They have been developed to complement the limitations of the conventional sensors such as electric resistance strain gauges, wired accelerometers, and extensometers, and to measure new types of structural characteristics such as electromechanical impedances and guided waves. Many researchers have been working on the realization of smart sensors for SHM on full-scale structures.

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2.1 Optical Fiber Sensors

The OFSs have various advantages that include durability, immunity to electromagnetic interference, lightweight, small size, high sensitivity, wide bandwidth, and ease in implementing multiplexed or distributed sensors. Strain, temperature, and pressure are the most widely measured quantities using OFSs. The Fiber Bragg Grating (FBG) sensor shown in Fig. 1 represents the most widely used technology among OFSs (Johnson *et al.*, 1999; Ryu *et al.*, 2002; Shu *et al.*, 2002; Kim *et al.*, 2003a, 2003b, 2005, 2010; Park *et al.*, 2007). Durability of OFSs has drawn much interest from the structural engineers, especially for long-term structural health monitoring. Although the cost of OFS systems is still the major concern, severe environmental conditions and the large scale of civil infrastructures make the OFSs beneficial alternatives for several structural systems such as a nuclear containment structure, long span bridges, railway bridges with high-voltage power lines, tall buildings, and pipeline systems. Recently, cost-effective systems including Brillouin Optical Time Domain Analysis (BOTDA; Kwon *et al.*, 2001, 2003, 2009; Zhou *et al.*, 2008) sensors and low-cost interrogators have developed and applied to monitor large civil infrastructures. The BOTDA sensor can cover a long range extended to over 100 km by a single optical line. Some of the related development and application activities on OFSs are as follows:

- Development of economical and multiple Fiber Bragg Grating (FBG) sensor systems using wavelength-swept fiber laser and code division (Ryu *et al.*, 2002)
- Vibration-based SHM using FBG sensors (Johnson *et al.*, 1999; Kim et al., 2010)
- Weigh-in-Motion measurement with FBG sensors (Kim *et al.*, 2003a)
- Retrofit of concrete structures using carbon fiber sheets with embedded FBG sensors (Kim *et al.*, 2003b)
- Structural integrity test for nuclear containment structures using FBG sensors (Kim *et al.*, 2005)
- Fiber optic accelerometer systems for monitoring vibration of large-size structures (Feng *et al.*, 2006)
- Damage localization techniques using strain mode shapes and modal flexibility (Park H-J. *et al.*, 2007)
- Improvement of capability of BOTDA sensors (Kwon I-B. *et al.*, 2001, 2003; Zhou *et al.*, 2008)
- Oil leakage monitoring for off-shore pipelines using BOTDA sensors (Kwon *et al.*, 2009)

2.2 Piezoelectric Sensors

Smart piezoelectric sensors have unique molecular structures that allow bidirectional electromechanical coupling between the electric field and the mechanical strain, and thus they can be used as both actuators and sensors simultaneously. Piezoelectric sensors such as piezoceramic (PZT; lead zirconate titanate) sensors, Macro Fiber Composite (MFC) sensors, and Polyvinylidene Fluoride (PVDF) sensors in Fig. 2 have been widely used in structural dynamics applications because they are lightweight, robust, inexpensive, and come in a variety of forms ranging from thin rectangular patches to complex shapes (Park *et al.*, 2003). Based on this functionality, piezoelectric sensors have been the most extensively used for both impedance-based damage detection (Giurgiutiu and Rogers, 1997; Tseng *et al.*, 2000; Zagrai and Giurgiutiu, 2001; Park *et al.*, 2003; Park *et al.*, 2006a; Mascarenas *et al.*, 2007; Overly *et al.*, 2007; Min *et al.*, 2010; Park *et al.*, 2010) and guided waves-based damage detection methods (Monkhouse *et al.*, 1997; Keilers and Chang, 1995; Diaz Valdes and Soutis, 2000; Osmont *et al.*, 2001; Kehlenbach and Das, 2002; Sohn *et al.*, 2003, 2009; Kim and Sohn, 2006; Park *et al.*, 2006b; Raghavan and Cesnik, 2007; An *et al.*, 2009). With the recent advances of signal processing techniques and the improvement of hardware including MEMS (MicroElectroMechanical Systems) technology and wireless data transmission, piezoelectric sensors become more attractive in on-line SHM as well as non-destructive testing. Some of the related researches and application activities are as follows:

- Development of a piezoelectric oscillator sensor to detect

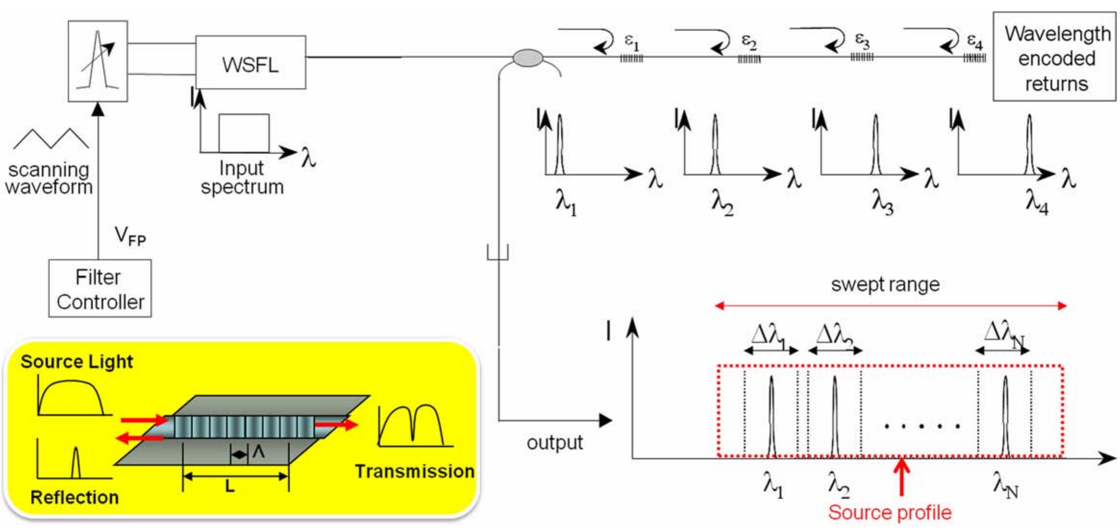


Fig. 1. FBG Sensor and Schematic of FBG Sensor System

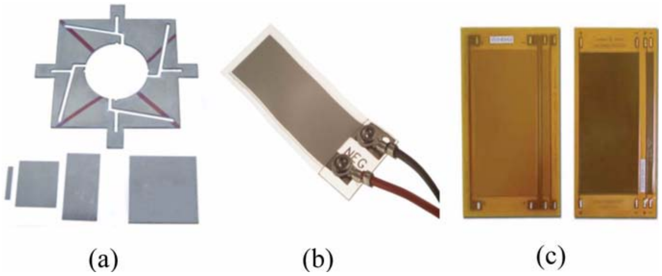


Fig. 2. Various Piezoelectric Sensors: (a) PZT Sensors (Piezo Systems, Inc.), (b) PVDF Sensors (Measurement Specialties, Inc.), (c) MFC Sensors (Smart Materials, Inc.)

damages on civil infrastructures (Kim *et al.*, 2005, 2008)
- Impedance-based damage detection on civil structures (Park *et al.*, 2006a)
- Reference-free crack detection using piezoelectric sensors (Sohn, 2003; Kim and Sohn, 2006)
- Piezoelectric sensor self-diagnosis using impedances (Park *et al.*, 2006, Park *et al.*, 2009)
- Smart dual PZT transducers for damage detection (Sohn *et al.*, 2009)
- On-line piezoelectric sensors-based SHM using wireless sensor nodes (Overly *et al.*, 2007; Park *et al.*, 2009; Park *et al.*, 2010; Zhou *et al.*, 2010)
- Various field applications using piezoelectric sensors-based sensing system (An *et al.*, 2009; Min *et al.*, 2010)

2.3 Wireless Smart Sensors

In case of conventional SHM systems, the expensive cost for purchase and installation of the system components including sensors, cables, data loggers, and computers is a big obstruction. For example, it has been reported that the Bill Emerson Memorial Bridge in the U.S. is instrumented with 84 wired accelerometers with an average cost of over $15,000 per channel (Wong, 2004) and the cost of the SHM system with 350 sensing channels on Tsing Ma Suspension Bridge in China has exceeded $8 million (Farrar, 2001). Given that the maintenance cost of the SHM system is an important consideration as the system gets older, wireless smart sensors have been regarded as an alternative tool for economical and accurate realization of SHM system. Wireless smart sensors have been developed considering the following essential features: sensing capability, on-board computation, wireless communication, self-powered, plug-in functionalities, and low cost. Low cost of wireless smart sensors enables dense arrays of sensors to be implemented on a large civil structure, so that the quality of the SHM can be dramatically improved with rich information which diagnosis algorithms can utilize to detect, locate, and assess structural damages. The wireless smart sensor technology has advanced significantly over recent years as shown in Fig. 3 (Straser and Kiremidjian, 1998; Lynch *et al.*, 2001 and 2006a; Aoki *et al.*, 2003; Chung *et al.*, 2004; Farrar *et al.*, 2005; Wang *et al.*, 2005). A number of commercial wireless smart sensor prototypes have been also developed for SHM

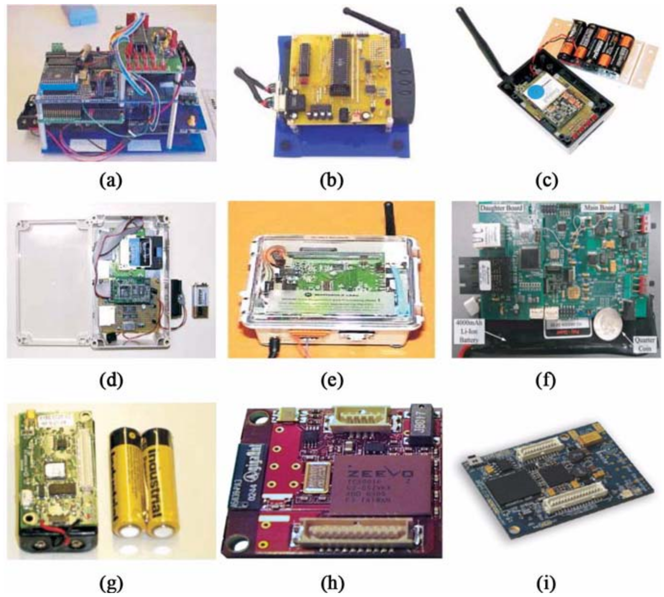


Fig. 3. Various Wireless Smart Sensor Prototypes (Cho *et al.*, 2008): (a) WiMMS (Straser *et al.*, 1998), (b) WiMMS (Lynch *et al.*, 2001), (c) WiMMS (Wang *et al.*, 2005), (d) RIMS (Aoki *et al.*, 2003), (e) Husky (Farrar *et al.*, 2005), (f) Dura-Node (Chung *et al.*, 2004), (g) MICA2 Mote (Crossbow), (h) Imote (Intel), (i) Imote2 (Intel)

applications. A Mote may be the most famous commercialized prototype, which is initially developed at the University of California-Berkeley and subsequently commercialized by Crossbow (Zhao and Guibas, 2004). It has been successfully complemented to iMote and iMote2 by Intel. iMote2s incorporating middleware services, which help civil engineers to easily generate application softwares using iMote2s, are being validated in full-scale civil structures by Spencer's group at University of Illinois at Urbana-Champaign (Nagayama *et al.*, 2006; Rice *et al.*, 2008; Jang *et al.*, 2010; Cho *et al.*, 2010).

2.4 Vision-based Displacement Measurement System

The displacement of a structure is usually considered as one of the major indicators to assess the structural integrity. It is, however, very difficult to directly measure the displacement of a large structure due to the accessibility to a reference point usually needed for conventional displacement sensors and the physical size of the structure. Recently, some promising advances have been made for displacement sensing including Global Positioning System (GPS, Knecht and Manetti, 2001), laser Doppler vibrometers (Nassif *et al.*, 2005) and vision-based systems (Wahbeh *et al.*, 2003). Among them, the vision-based method is a promising alternative to the conventional displacement method as the optic devices become affordable with rapid advancement in electronics and computer technology.

Lee and Shinozuka (2006b) developed a real-time displacement measurement system using digital image processing techniques. The system is cost-effective and easy to use, yet uniquely capable of measuring dynamic displacement with a high level of resolu-

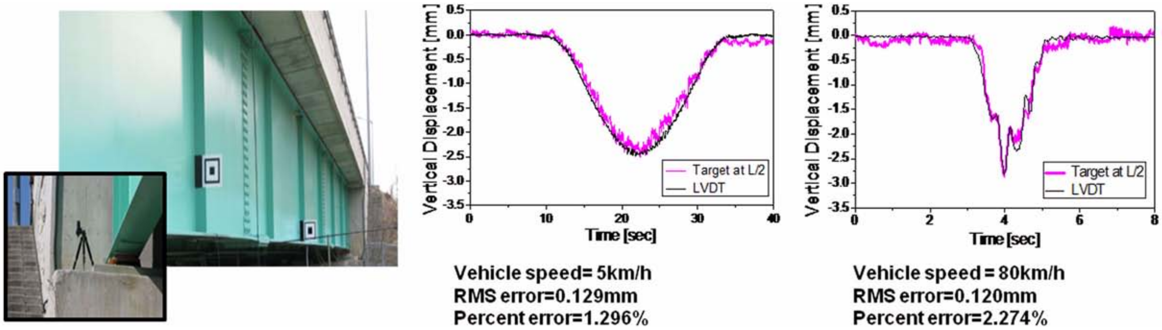


Fig. 4. Displacement Measurement using Digital Image Correlation Techniques

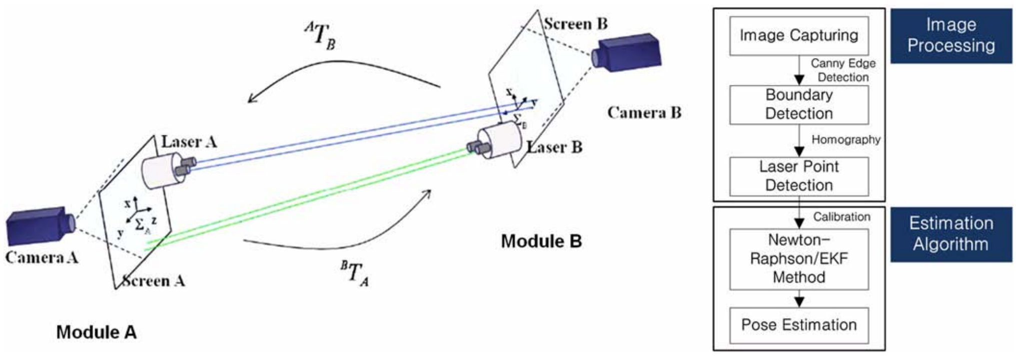


Fig. 5. A Schematic Diagram and Estimation Process of Paired Vision-based Displacement Measurement System

tion. The camera-based displacement measurement system has been applied to estimate load carrying capacity of a steel girder bridge (Lee *et al.*, 2007b), and has been extended to measure the displacement of a high-rise building structure using a novel partitioning approach (i.e., successive estimation of relative displacements and rotational angles throughout a large flexible structure). Kim *et al.* (2009) developed a novel technique to measure multi-point dynamic displacement of structures using digital image correlation technique and sub-pixel enhancement algorithms. Field tests have been made on a steel girder bridge and the test results showed good agreements with the conventional transducer (Fig. 4). Myung *et al.* (2010) developed another vision-based approach that incorporates a multiple paired Structured Light (SL) system which uses two lasers and a camera in pair in order to measure the accurate relative displacement between any two locations on the structure. The Newton-Raphson and extended Kalman filter-based displacement estimation methods were implemented by deriving a kinematic equation and its constraints (Fig. 5).

3. Smart Monitoring and Damage Assessment

SHM methods can be categorized into two approaches: global and local monitoring. For global health monitoring, the acceleration responses are commonly measured, and the modal properties are extracted thereafter (Kim *et al.*, 1995, 2003, 2007; Yun *et al.*, 1997, 2000; Feng *et al.*, 1998; Jang *et al.*, 2002; Kwon *et al.*, 2003; Yi *et al.*, 2004; Kang *et al.*, 2005; Park *et al.*, 2007; Shin and Oh, 2007; Choo *et al.*, 2009). Then, the results are compared with the baseline data, which may assess the overall safety of the structure. However, the number of sensors in the sensor array is generally limited to cover the entire structure and the modal information is often not sensitive enough to detect damage occurred locally. To overcome this problem, local monitoring on selected critical areas shall be combined with global monitoring. This section introduces the research trend on smart global and local monitoring systems and damage assessment techniques.

3.1 Vibration-based Global Monitoring Techniques

Vibration-based SHM procedure may be divided into two parts: data processing of the measured data for feature extraction and information processing of the extracted feature for damage identification. The damage identification has been traditionally carried out by minimizing the estimation error in the modal properties regarding the element level damage indices. The advance in the soft computing techniques such as Neural Network (NN) and outlier analysis techniques offers great advantages for on-line global monitoring with its excellent pattern recognition capability (Yun and Bahng, 2000; Lee and Yun, 2007a). Lee *et al.* (2002, 2005) presented a NN-based damage estimation of a bridge structure as in Fig. 5, which is based on the changes in the modal properties extracted from the ambient vibration data under traffic loadings. Here, a reduction of bending stiffness in a structural member was considered as damage. An improved algorithm was proposed to consider the modeling errors in the baseline finite element model, from which the training patterns were to be generated.

The mode shape differences between before and after damage, instead of the mode shapes themselves, were used as damage features to relieve the effect of the inevitable modeling errors. A field validation was performed on a span of the old Hannam Grand Bridge over Han River in Seoul, Korea to confirm the applicability of the NN-based approach.

The changes in the modal flexibility can be utilized for damage estimation of the structure instead of the stiffness changes (Madhwesh and Ahmet, 1992). Zhao and DeWolf (1999) showed that the modal flexibility is more sensitive for damage detection than the natural frequencies and mode shapes. Several damage detection methods have been proposed, which uses changes in modal flexibility (Pandey and Biswas, 1994), curvatures of the uniform load surface (Zhang and Aktan, 1995), or anomaly in the uniform load surface (Toksoy and Aktan, 1994). Koo *et al.* (2008) proposed a new method in which anomaly in the uniform load surface calculated by modal flexibility was treated as a damage feature. It is based on the explicit relationship between the damage and the damage-induced deflection and constructs a simple mapping from the damage-induced deflection to the actual damage location. Tomaszewska (2010) considered the effect of statistical errors in order to distinguish between true and false damage detection results, based on structural flexibility and modal curvature approaches.

Vibration-based monitoring and damage detection techniques have been applied to the evaluation of the load carrying capacity of bridge. Their approach is based on the traffic-induced ambient vibration data as dominating signals in the bridge (Kim *et al.*, 2001; Lee *et al.*, 2002; Lee *et al.*, 2005; Yi *et al.*, 2007). Therefore no traffic blockage is needed. Environmental effects including temperature, vehicle-bridge interaction effects, and supporting conditions were considered for more reliable evaluation of load carrying capacity. The approach consists of (1) ambient vibration tests on a bridge; (2) identification of modal properties extracted from the ambient acceleration data; (3) enhancement of the initial FE model of the bridge structure based on the identified results; and (4) estimation of the load carrying capacity using the updated FE model. The proposed approach has been validated on various types of bridges by cooperative researches between academia and the bridge authorities in Korea (Yun *et al.*, 2009b).

3.2 Decentralized SHM using Wireless Sensor Networks

The conventional sensory systems usually collect and process the measured data in the centralized way. All the raw data from sensors are transferred to the data logger and processed by the central computing device, commonly called a server. The centralized processing, however, has a limitation of data inundation and low fault-tolerance caused by long cables. The wireless smart sensors can form a sensory network, called a Wireless Smart Sensor Network (WSSN), and it enables the decentralized processing fully utilizing the computing capability of wireless smart sensors. The decentralized processing starts from dividing the full network into several local networks, called clusters, and forming a hierarchical network of wireless smart sensors according to the sensor's performances such as fault tolerance, radio accessibility, computing capability, and power supplier. The concept of hierarchical decentralized processing is shown in Fig. 7. An autonomous decentralized SHM system with a concept of the distributed implementation of vibration-based damage detection algorithms has been suggested by Gao and Spencer (2008), which is based upon the distributed computing strategy. Nagayama *et al.* (2007) has realized the autonomous decentralized SHM system using iMote2 wireless smart sensor prototype incorporating with TinyOS (Levis *et al.*, 2005), middleware services, and a flexibility-based damage detection algorithm. Zimmerman *et al.* (2009) has proposed a decentralized modal analysis scheme using chain-like topology of the wireless smart sensor network with frequency-domain output-only modal analysis techniques, and it has been implemented to extract modal properties of a

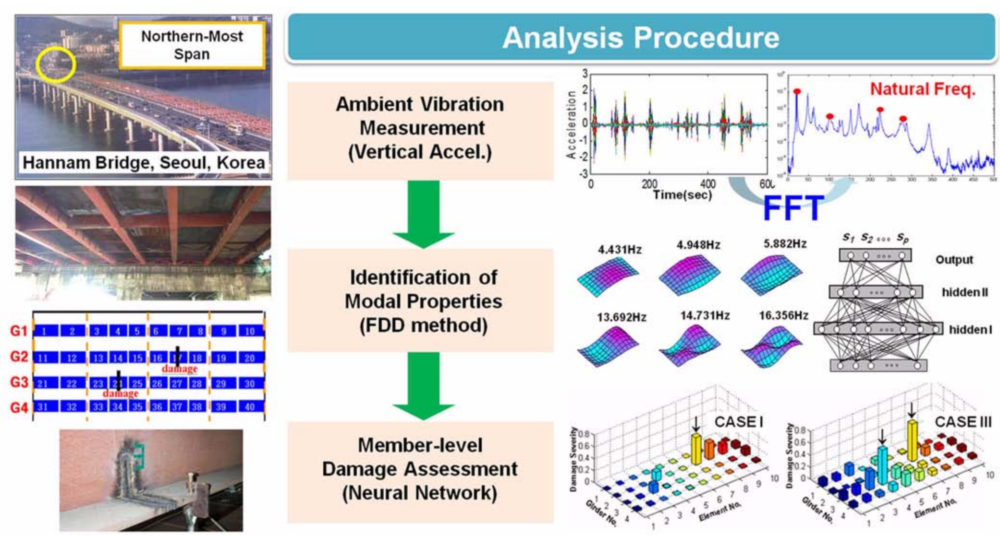


Fig. 6. Vibration-based Damage Detection on Hannam Grand Bridge (Lee *et al.*, 2002)

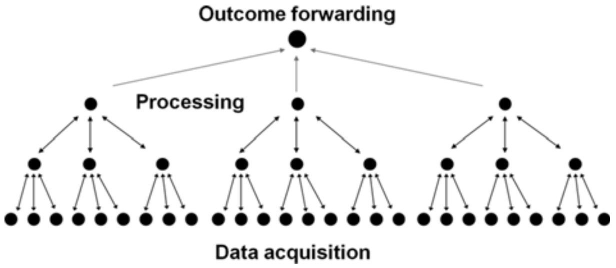


Fig. 7. Decentralized Processing Scheme (Nagayama *et al.*, 2010)

historic theatre. Sim *et al.* (2010) has developed decentralized data aggregation, which processes cross-correlation function or random decrement functions in several preset clusters to reduce the bandwidth of transmitted data, to determine the global modal properties with high fidelity. They are all validated in a laboratory-scale truss structure. Different with the above approaches, Zimmerman *et al.* (2009) has succeeded to update the FE model of a 3-story shear building structure using wireless smart sensor network with embedded parallel simulated annealing algorithm.

3.3 Local SHM using Piezoelectric Sensors

The SHM schemes using the piezoelectric sensors can be broadly classified into two different types of active sensing-based techniques: electromechanical impedance-based methods and guided waves-based methods. Electromechanical impedance-based techniques have been developed as a tool for real-time structural damage assessment on critical members of large structural systems such as bridges, pipe lines, buildings, and power plants (Giurgiutiu and Rogers, 1997; Tseng *et al.*, 2000; Zagrai and Giurgiutiu, 2001; Park *et al.*, 2003; Park *et al.*, 2006a). The basis of this active sensing technology is the energy transfer between the actuator and the host mechanical system. A change in the structure's mechanical impedance directly results in a change in the electrical impedance measured by the piezoelectric sensor. Since damages cause a change in the structure's local mass, stiffness, or damping properties and consequently its mechanical impedance, the structure's mechanical integrity can be assessed by monitoring the electrical impedance of the piezoelectric sensor. For quantitative assessment of damage, scalar damage indices such as Root Mean Square Deviation (RMSD), Cross-Correlation Deviation (CCD), Mean Absolute Percentage Deviation (MAPD), and covariance change are used (Park *et al.*, 2003). Recent advances in online SHM, including actuation and sensing, on-board computing, and Radio-Frequency (RF) telemetry, have improved the accessibility of the impedance method for in-field measurements. Research groups at Los Alamos National Lab developed a compact impedance-based wireless sensing device and extended its capability by implementing a module with low-frequency A/D-D/A converters to measure low-frequency vibration data for multiple SHM techniques (Mascarenas *et al.*, 2007, 2009; Overly *et al.*, 2007, 2008; Taylor *et al.*, 2009a,b). A phase-based wireless impedance sensor node was developed by research groups at Virginia Tech to minimize the required power eliminating a digital-to-analog converter and Fast Fourier Transform operation (Park, 2003; Grisso *et al.*, 2005; Kim *et al.*, 2007a,b; Zhou *et al.*, 2010). Wireless impedance sensor nodes were applied to detect loose bolts and crack damages on real steel bridge and building structures as well as damages on lab-scale structures (Park *et al.*, 2009; Min *et al.*, 2010, Park *et al.*, 2010). The results showed that the impedance sensor nodes had a big potential for local wireless health monitoring of structural components and for constructing a low-cost and multifunctional SHM system as "place and forget"

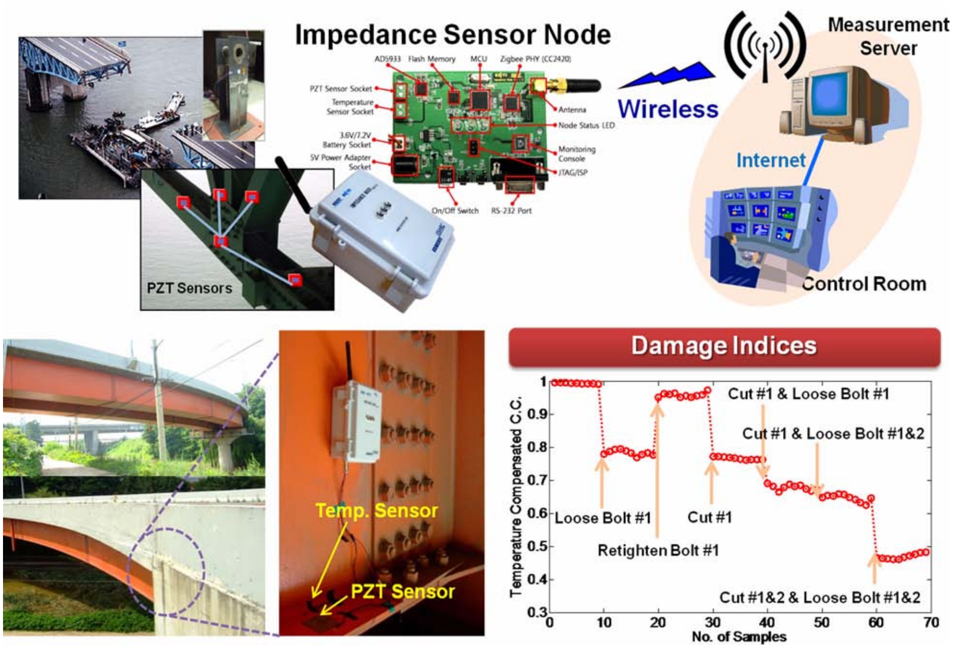


Fig. 8. Wireless Impedance Sensor Node for Damage Detection on Bridge (Min *et al.*, 2010)

wireless sensors (Fig. 8).

Guided waves-based damage estimation techniques have become popular Nondestructive Testing (NDT) and SHM approaches due to the sensitivity to small defects and long cover range with little attenuation (Cawley and Alleyne, 1996; Draeger *et al.*, 1997; Ghosh *et al.*, 1998; Sohn *et al.*, 2003, 2007; Kim and Sohn, 2006; Park *et al.*, 2006a,c; Raghavan and Cesnik, 2007). In guided waves-based SHM, the actuator is operated to generate guided waves by high-frequency pulse signal. When a guided wave field is incident on a structural discontinuity which has a size comparable to the wavelength, it scatters guided waves in all directions. The discontinuity in the structure would be crack, delamination, change in structural dimension, and a structural boundary. To distinguish damages from the others, prior information is required in structure's undamaged state. Recently, a new baseline-free methodology was proposed for the guided waves-based method to detect crack damages in a thin structure without using prior baseline data or a predetermined decision boundary (Sohn *et al.*, 2007). It utilizes the polarization characteristics of the PZT sensors attached on both sides of structure. Since a sudden change in the thickness of the structure due to crack formation creates Lamb wave mode conversion, the appearance of the crack can be extracted based on this mode conversion from measured Lamb waves. A new type of PZTs, called a dual-PZT has been recently developed for easy and effective placement of sensors for actuation and sensing (Sohn *et al.*, 2009; An and Sohn, 2010). The applicability and robustness of the baseline-free technique using dual PZTs was validated in the decommissioned bridge and showed considerable results for crack detection located between two dual-PZTs (An *et al.*, 2009).

3.4 Wireless Power and Data Transmission

In case of wireless active sensing devices such as PZT transducers, relatively high electrical power is required compared to conventional passive sensors such as accelerometers and strain gauges (Yeatman, 2009). Although extensive research work has been focused on energy harvesting, the amount of harvested energy often falls below the levels need for active SHM sensing systems (Park *et al.*, 2008). Therefore, several studies on alternative power supply schemes have been explored.

One approach is to employ Radio Frequency (RF) microwave transmission technologies (Brown, 1996) to wirelessly transmit the power to an active sensor node, where RF microwaves are transmitted across the atmosphere or space to a receiver (rectifying antenna) to receive and directly convert the microwaves into DC power. Mascarenas *et al.* (2007) used wireless RF transmission to deliver electrical energy to power a piezoelectric impedance sensor node by charging the capacitor in the node. The results showed good performance by transmitting necessary power to the impedance sensor node, and it took about 200 seconds to reach up to operation voltage level (3.3 V) of the node. However, one of the limitations in microwave transmission was the attenuation of the wave as it travels through space. The loss associated with this attenuation has been characterized as the square

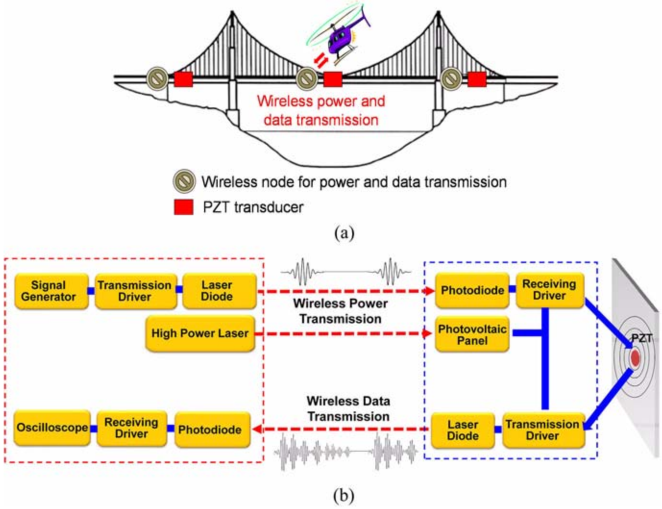


Fig. 9. Optics-based Wireless Guided Wave Generation and Sensing (Park *et al.*, 2010): (a) Schematic of Wireless Actuation and Sensing, (b) An Overall Schematic

of the distance between the transmitting and receiving antennas. Park *et al.* (2010) proposed an optical system for wireless power and data transmission (Fig. 9). It took advantage of optoelectronics for both guided wave generation and sensing. A generated waveform by modulation of a laser is wirelessly transmitted to a photodiode connected to a PZT on the structures. Then, the photodiode converts the light into an electrical signal and excite the PZT and the structure. Finally, the reflected response signal received at the same PZT is re-converted into a laser, which is wirelessly transmitted back to another photodiode located in the data acquisition unit for damage diagnosis. Since the laser emits highly directional and collimated radiation with a low angle of divergence, the energy carried by the laser beam can be transmitted for a long distance without attenuation and focused onto a small area.

3.5 Energy Harvesting and Management

Though self-powering of wireless smart sensors avoids the effect of AC power-line network on composition of sensor network and electric surge in the outdoor use, it also causes one of the major challenges in wireless systems, sustainable power supply. Recently, there has been a surge of research in the area of energy harvesting, which has been brought on by the advances in wireless technology and low-power electronics. Once the battery has consumed all of its power, replacement of the battery located remotely can become a very expensive and tedious, or even impossible task. Thus, many researchers in the SHM and sensing network community have shown interest in power harvesting, and have proposed alternative power sources such as sunlight, thermal gradient, human motion, and vibration (Glynne-Fones and White, 2001; Roundy, 2003; Qiwai *et al.*, 2004; Sodano *et al.*, 2004; Mateu and Moll, 2005; Paradiso and Starner, 2005). Among them, the solar and vibration energy is the strongest candidate for application to the civil infrastructures as shown in

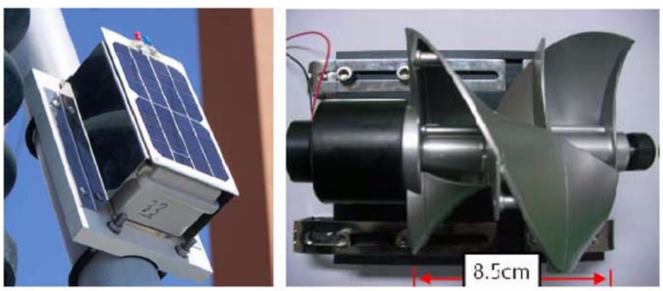
Table 1. Typical Data for Various Energy Harvesting Techniques (Mathuna *et al.*, 2008)

Energy Source	Condition	Power density [μW/cm^2]	Energy/day [J]
Solar	Outdoors	7500	324*
Solar	Indoors	100	4.32*
Vibration	1 m/s^2	100	8.64
Thermal	ΔT = 5ºC	60	2.59*

*Note: assuming light is available for 50% of the time.

Table 1 (Mathuna *et al.*, 2008). One another promising energy source is wind power in long span bridges, which are usually located in windy area. Park *et al.* (2010) investigated the feasibility of small wind-powered generators to operate wireless smart sensors located at a cable-stayed bridge to show the maximum output power of 27.3 mW at 3.0 m/s of wind speed.

In lieu of energy harvesting, there have been several researches to minimize the battery usage under the same operating configuration of wireless smart sensors. Since the wireless data transmission generally consumes more power than local computation of data, the data processing and compression by local interrogation of measured data has been widely studied to reduce the power consumption caused by wireless transmission. For example, Lynch *et al.* (2003) has embedded many SHM algorithms, such as Fast Fourier Transform, Auto-Regressive, Random Decrement, and Frequency Domain Decomposition, into the computational core of wireless smart sensors to reduce the wide bandwidth of time-history vibration data. The local interrogation scheme has been applied to most of wireless smart sensor applications (Cho *et al.*, 2010; Sim *et al.*, 2010). Rice *et al.* (2010) have proposed a flexible framework for autonomous full-scale SHM of large civil structures to minimize the power consumption in a large-scale wireless sensor network. All the sensors are set in the sleep-mode in the default condition and wake up when several preset sentry nodes, that are woken up, periodically to sense data for a short period of time, measure the data exceeding preset threshold values.



(a) (b)

Fig. 10. Energy Harvesters: (a) Solar Panel on Sensor Node (Jang *et al.*, 2010), (b) Blade of Small Wind Turbine (Park J. *et al.*, 2010)

4. Recent Cooperative R&D Activities on SHM Test Beds

4.1 Korea-US Collaborative Research for Bridge Monitoring Test Beds

The Korea Expressway Corporation (KEC) has constructed a test-road section of 7.7 km long in parallel to the Jungbu Inland Expressway near Icheon, South Korea (Fig. 11) in order to investigate the long-term behavior of highway pavement systems with a number of different designs exposed to the traffic and severe weather condition. For a Korea-US collaborative research to explore emerging smart sensors and sensing tools on bridges, three bridges on the test-road were selected as test beds with the agreement of the KEC. A series of collaborative field tests have been performed using piezoelectric sensors (KAIST, Sungkyunkwan Univ., Univ. of Maryland), wired and wireless accelerometers (KAIST, KEC, Michigan Univ., and Univ. of California-Irvine), wireless active sensors (KAIST), and vision-based vibration monitoring system (Sejong Univ.) since 2008. Various sensing systems have been deployed on the testbed bridges where the internet access was provided for participants so that instruments and measurement systems can be accessed remotely using Remote Desktop software. Each participating group validated the feasibility of their own sensors and data/information processing algorithms (Lee *et al.*, 2006a, 2006b, 2007b; Lynch *et al.*, 2006b; Yun *et al.*, 2009b; An *et al.*, 2009).

4.2 Wireless Vibration Sensor Network for Bridge Monitoring

Wireless smart sensors are on the way of practical use for actual SHM of civil structures. Many researchers have employed wireless smart sensors for the bridge monitoring to provide important insight into the opportunities and challenges of state-of-the-art wireless smart sensor technologies (Lynch *et al.*, 2006b; Kim et al., 2007; Cho *et al.*, 2010; Jang *et al.*, 2010; Pakzad *et al.*, 2010). An international test bed for state-of-the-art wireless smart sensor technology has been developed on a cable-stayed bridge in Korea (The second Jindo Bridge) through a trilateral collaborative research among Korea (KAIST, Seoul Nat'l Univ., Sejong Univ.), the US (Univ. of Illinois at Urbana-Champaign), and Japan (Univ. of Tokyo). The wireless vibration-based SHM is introduced mainly in conjunction with the collaborative research in this section. For specific information, the following literatures can be referred: Rice *et al.* (2010), Jang *et al.* (2010), Cho *et al.* (2010), and Nagayama *et al.* (2010).

The key component of the wireless smart sensors used in this research is iMote2 (MEMSIC, 2010), and it is stacked with a sensor board and a battery board as shown in Fig. 12. Two types of sensor boards, SHM-A and SHM-W sensor board have been developed by University of Illinois at Urbana-Champaign. SHM-A multi-scale sensor board is developed to measure 3-axis acceleration as well as temperature, humidity, and illuminance, whereas SHM-W sensor board is to measure wind speed and direction interfaced with an ultrasonic anemometer. The flexible frame-

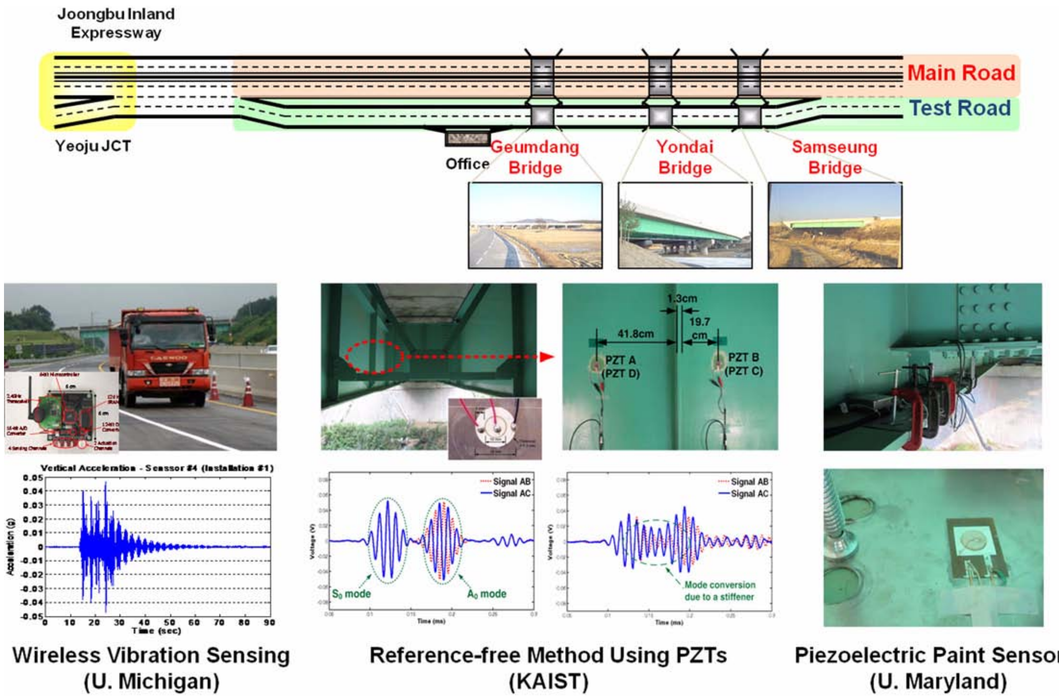


Fig. 11. Korea-US Collaborative Research on Test Beds

work for large-scale wireless smart sensor network proposed by Rice *et al.* (2010) are implemented in this research to minimize the power consumption of wireless smart sensors and automate the operation of SHM system.

Total of 70 wireless smart sensor nodes were deployed on the bridge, and they mainly measure 3-axis acceleration, except one wind-sentry node with an anemometer. Fig. 12 shows the locations of 70 nodes. The whole network is composed of two sub-networks controlled by different base stations. Jindo sub-network consists of 33 nodes with 22 nodes on the deck, 3 nodes on the pylon, and 8 nodes on the cables, whereas Haenam sub-network consists of 37 nodes with 26 nodes on the deck, 3 nodes on the pylon, and 7 nodes on the cables. Most of the nodes were powered by 3 D-cell batteries with 21500 mAh capacity, while 8 nodes (2 nodes on the tops of both pylons, and 5 cable nodes and 1 deck node of the Haenam sub-network) were powered by solar panels with rechargeable batteries to test the sustainable energy harvesting.

For output-only modal analysis, the Stochastic Subspace Identification (SSI) method (Overschee *et al.*, 1993) was employed to identify the modal properties using the acceleration data from the wireless smart sensor network. The modal analyses were independently carried out on the data from two sub-networks and combined subsequently. In Table 2, the natural frequencies obtained from the wireless system show excellent agreements with those obtained from the wired monitoring carried in 2007. They are also very close to those from FE analysis up the third vertical modes, while those for the higher modes are generally larger than FE results. The global mode shapes were constructed as shown in Fig. 13, and they showed good agreements with the FE

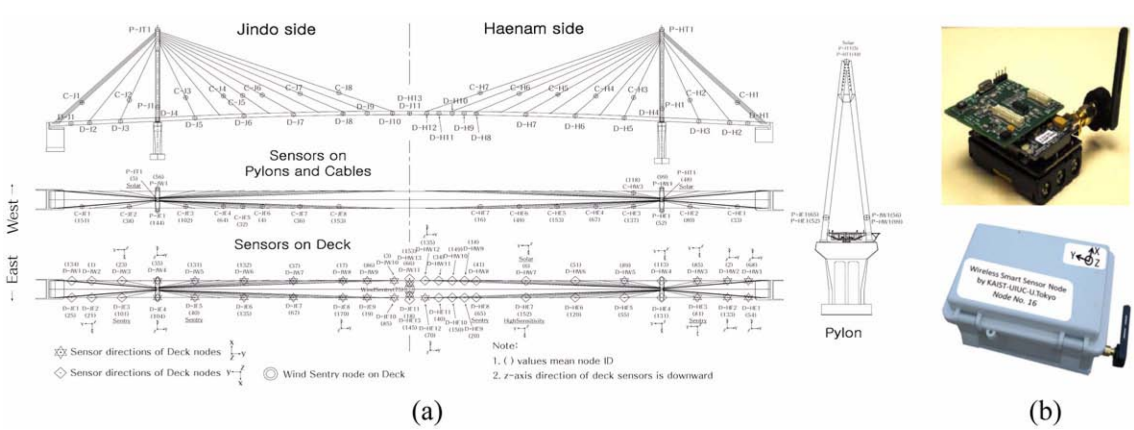


Fig. 12. Sensor Nodes Deployed on the Second Jindo Bridge (Jang *et al.*, 2010): (a) Sensor Locations, (b) Sensor Node

Table 2. NaturaL Frequencies using Wireless, Wired Monitoring System, and FE Analysis

Modes	WSSN (Hz)		Wired system (Hz)	FE analysis (Hz)
	Haenam sub-network	Jindo sub-network		
DL1	0.2998	0.2985	-	0.3137
DV1	0.4347	0.4380	0.4395	0.4422
DV2	0.6619	0.6439	0.6592	0.6471
DV3	1.0371	1.0364	1.0498	1.0010
DV4	1.3481	1.3555	1.3672	1.2472
DV5	1.5755	1.5759	1.5869	1.3490
DV6	1.6618	1.6660	1.6602	1.4596
DT1	1.8278	1.8410	-	1.7888
DV7	1.8844	1.8860	1.8555	1.5858
DV8	2.2712	2.2731	2.3193	2.1154
PB1	2.4107	2.3890	2.3682	2.1392
DV9	2.8127	2.8266	2.8076	2.5612

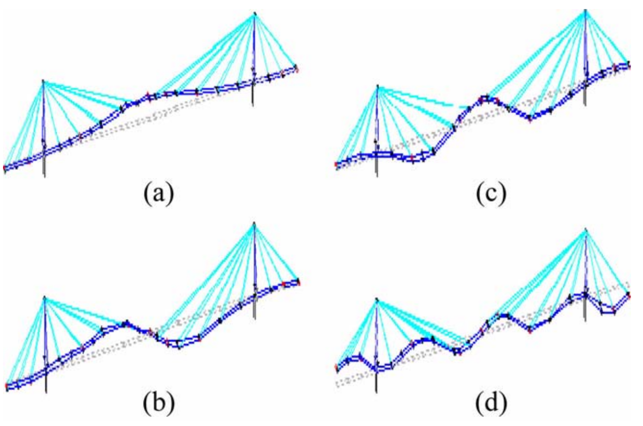


Fig. 13. Example Mode Shapes and MAC Values Correlating to FE Model Analysis (Cho *et al.*, 2010): (a) DV1 (MAC: 0.957), (b) DV2 (MAC: 0.986), (c) DV3 (MAC: 0.975), (d) DV6 (MAC: 0.949)

analysis results with modal assurance criterion (MAC) values of 0.943-0.986.

4.3 SHM Systems for Railroad Bridges

Recently a challenging project has been carried out for construction of a national network for safety management and monitoring for civil infrastructures in Korea. Fig. 14 shows an overall schematic of the project, in which total 32 real-time SHM systems are constructed on various types of testbed structures including bridges, cut slops, tunnels, embankments, and water supply systems, etc, and integrated through on-line internet networks. Thus, the behaviors of the testbeds can be monitored at the monitoring center. If structural damages or abnormalities are detected by the system, it is expected to send alarm messages to the maintenance offices and the related authorities in the form of SMS (Short

Fig. 14. Overall Schematic of National Networks for Safety Management and Monitoring of Civil Infrastructures (*KISTEC: Korea Infrastructure Safety & Technology Corporation)

Messaging Service). More detailed description of the project can be found in the references (KISTEC, 2007; Kim *et al.*, 2009; Heo *et al.*, 2009).

As a part of the project, SHM systems have been established on several railroad bridges. The system comprises various sensors, a local site server, and a main processor at the control center. The sensors measure real-time responses from a railroad bridge under train-transit and environmental loadings. Measured data are collected to a local server located at a remote place, and automatically transmitted to the control center via the internet. This monitoring system can be remotely accessible and controllable with the commercial internet service.

Fig. 15 shows one of the SHM systems on Han River railroad bridge, which is the biggest steel truss bridge in Korea. Total 46 sensors were installed including 16 accelerometers for vibration monitoring, 18 FBG sensors for structural strain monitoring on the girder, 2 FBG sensors for temperature monitoring, 5 wireless impedance sensor nodes with 10 PZTs on bolted joints. Currently long-term behaviors of the railroad bridge testbeds are being investigated, and guidelines for safety management are to be established by combining numerical analysis and signal processing of the measured data.

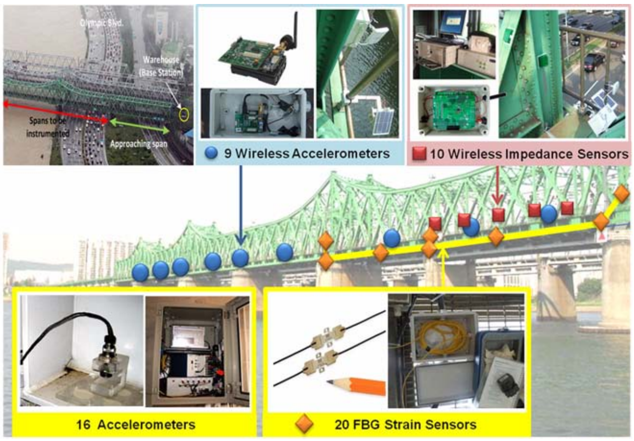


Fig. 15. SHM System on Han River Railroad Bridge

5. Conclusions

In this paper, recent R&D and application activities on smart sensing, monitoring, and damage detection for civil infrastructures were briefly introduced. Smart sensors such as optical fiber sensors, piezoelectric sensors, and wireless sensors were first introduced. Then, recent advances in the structural monitoring techniques are introduced, particularly on ambient vibration-based bridge monitoring/assessment, global damage assessment using soft computing algorithms, wireless sensor networks without data collision and excessive energy consumption, local damage detection using wireless impedance sensor nodes, guided waves-based crack damage detection using piezoelectric sensors, wireless power transmission methodology using laser/optoelectronic devices, and energy harvesting systems adapted for civil infrastructures. Finally, recent multi-disciplinary and international collaborative R&D activities on smart sensors and monitoring technologies are presented. For actual applications of smart monitoring technologies apart from academic research activities, testbed bridges have been established on various types of bridges including cable-stayed bridges and railroad truss bridges, so that participating researchers may bring their sensing systems to validate and enhance their technologies through the active research collaborations.

Acknowledgements

This work was jointly supported by the Smart Infra-Structure Technology Center (SISTeC) at KAIST sponsored by the National Research Foundation (Grant No. R11-2002-101-03001-0) and the 2006 C&T Innovation Program (Grant No. 06coretech-B05) sponsored by Ministry of Land, Transport and Maritime Affairs of Korean Government. Their financial supports are greatly appreciated. Finally, the authors would like to thank Dr. Hoon Sohn, Dr. Hyungjo Jung, Mr. Soojin Cho, and Mr. Hyun Jun Park at KAIST for providing up-to-date materials on smart sensing technologies for this paper.

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