Design and laboratory performance verification of a wireless transmitting system for structural health monitoring

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ABSTRACT: Structural Health Monitoring for civil structures has recently become an area of great activity in both the research community and public sector. A good Structural Health Monitoring System requires the sensor to have the following merits: cheap; durable; easy and simple to install and maintain; wireless; no battery replacement needed for operation; smart. To obtain the aims, a task effort has been made towards to developing a wireless monitoring system. In this paper, a wireless unit for real-time structural response measurements has been designed and fabricated. Drawing upon advanced technological developments in the areas of wireless communications, low-power microprocessors and transmitting-incepting unit and sensing transducers, the wireless unit represents a highly-performance but lower-cost measure of monitoring performance of structures in the short-term and long-term. This system can be used in the prudent allocation of emergency response resources after earthquakes and for damage identification of structures under long-term deterioration and excessive loadings.

1 INSTRUCTION

Due to a wide variety of unpredictable conditions and surroundings, it will be impossible and unpractical to design and construct a structure whose probability of failure is a zero percent. In terms of the aims of structural health diagnosis, damage identification method defines four levels of damage identification as follows(Rytter 1993): Determination that damage is present in the structure; determination of the geometric location of the damage; quantification of the severity of the damage; prediction of the remaining service life of the structure. Great amount of sensors monitoring the structural health condition and response under different external loads must be installed on civil engineering structures. According to Housner et al.(1997), structural health monitoring can be defined as "the use of in-situ, nondestructive sensing and analysis of structural characteristic, including the structural response, for detecting changes that may indicate damage or degradation". But for modern structural health monitoring the definition by Housner et al.(1997) can be modified as "the use of in-situ, nondestructive sensing and analysis of structural characteristics, including the structural response and modal parameters, for the aims of finding whether damage has occurred or not, determining the damage localization, identifying the damage degree and evaluating the remaining load-carrying capacity and remaining service life". The original intention of structural health monitoring system installed on civil structures was also to instrument the structural response during strong ground motions. The records of structural response and strong ground motion colleted through this typical idea can make us comprehend strong ground motion, structural effect that earthquake brings and structural designation in great intensity region more profoundly. The early structural health monitoring system is installed on such important and large-scale structure as hospital, large-scale dam and long-span bridges. Up to present, many countries in worldwide install structural health monitoring system on long-span bridges. In California, damage detection tests on site were carried on 61 long-span bridges with 900 different types sensors (Hipley 2001), then California Ministry of Transportation verified all the validate design model of the bridge that they ruled with measurement response, in order to take action to meet an emergency for abrupt strong earthquake. In Europe, external load and long-term distortion of the concrete bridges were monitored by using fiber strain sensors (Inaudi and Vurpiuot 1999). In Asia, structural health monitoring systems were installed on many large-scale bridges during their initial construction such as the Akashi Kaikyo and Tatara bridges in Honshu of Japanese (Tamura 2001). In order to illustrate the applied extension of current health monitoring systems installed on bridge, the Ting ma bridge in Hong kong built in 1997 completely is cited as an example. The length of the longest span of Ting ma bridge is 1377 meters, it is a center of 6 important transport routes. During its initial construction, structural health monitoring system is made up of 350 different types sensors installed on the Ting ma bridge (Ni et al. 2001). Thereinto, the sensors selected to measure all kinds of bridge responses included accelerator sensors, anemometers, strain gages, thermometers and displacement sensors. Anemometers were used for measuring wind speed of bridge deck and main towers location, thermometers were used for recording bridge environmental temperature, accelerate sensors were used for measuring bridge responses under all kinds of external loads.

Current structural health monitoring systems designed for civil engineering structures make use of wires to transmit the measured signal from the sensors (accelerometers and strain gages) installed on the structures to a data processing center. Such structural health monitoring system is proved to be a reliable and accurate system, but their installation costs are very high. Generally, the structures such as long-span bridges are situated in wicked storm environments or in other harsh weather environments, additional installation costs that proof the wire not to be eroded increase.

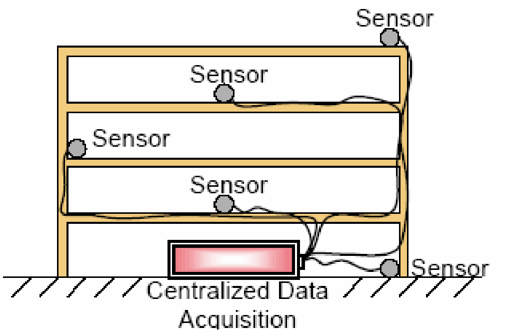

Fig. 1 Central wire-based structural monitoring systems(Cited from J.P. Lynch)

2 WIRE-BASED HEALTH MONITORING SYSTEM

Modern structural health monitoring system includes four aspects as follows：(1) sense capabilities; (2) data processing; (3) baseline and quantification; (4) structural prognosis. In recent 2 decades, the vast majority of published work on monitoring civil structures has focused on developing algorithms to advance the detection and diagnosis of damage to structures. That is to say, the third and the last aspects are emphasized. From the first aspect, current monitoring systems make use of conventional cable-based sensors to transmit their measurements to a processing center. The monitoring system based on signal cables for civil structures (see Figure 1) has a higher installation costs and the signal wires are vulnerable to environment noise corruption. And the sensors are lack of processing self-collecting data, they collect data only. So, the function of central data processor is collecting, memorizing and processing the data measured. The recent research in structural health monitoring centralized in how to process the data measured and damage identification techniques with the disposal results of these data (Bergmeister and Sanfa 2001). Structural health monitoring system comprising of tens of even hundreds of transducers has very poor measurability, moreover, the installation costs is becoming increasingly expensive for every channel. Nowadays, the total installation costs of structural health monitoring system in civil engineering structures are very expensive. As an instance, the installation cost of structural health monitoring system on the Tsing Ma long-span bridge was almost $27000 per channel (Farrar 2001). In the same way, in Europe, the cost of installing fiber health monitoring system on 200-meters-span concrete bridge ranges from $20 thousand to $100 thousand (Bergmeister 2000). For most bridge structures, bridge inspections are required every year to find the symptom of structural fatigue or damage. The total inspection cost accounts for 0.05 percent to 1 percent of the total cost of bridge construction. And the total cost to repair and to reinforce the bridge is the same as 4 percent of the total construction cost of the bridge. Using condition-based repair instead of the schedule inspection, inspection costs will be decreased remarkably, moreover, the repair costs will be reduced to 0.1 percent of the total construction costs. One direct reason that the total costs of structural health monitoring system are high is that the installation and maintenance costs of the transferring cables in the system are remarkable. Time and cost occupancy proportion for cables in the installation process should be that over 75 percent of the total system installation time is spent on installing the cables that the installation cost accounts for 25 percent of the total system installation cost only (Straser and Kiremidjian 1998). Moreover, in outdoors, in order to resist harsh conditions additional expenses spending on protecting the transmit cable from eroding, as makes the cost high more. Because of the high installation and maintenance costs, the owners who apply structural health monitoring technique to their belongings are fewer and fewer. Up to the present, only those structures identified as important by most of the researchers possesses the installation cost of structural health monitoring system. Nowadays, the demand of structural health monitoring system is increasing because of the advanced technology. Especially, many algorithms identifying damage in structures were successfully developing by many scholars (Doebling et al. 1996; C. R. Farrar et al. 1999; Farrar, C.R. and Sohn 2001;H.H. Sohn and K. H. Law, 2000, 2001a, 2001b).

3 DESIGN OF WIRELESS TRANSMISSION SYSTEM

For the sake of catching more information of the structural health state, it is necessary that several hundreds of sensors be installed on the large-scale civil engineer structure. For so many sensors installed on the structures, it is integrant to consider following critical problems: (1) cheap; (2) low power consumption, for example, no battery replacement needed for operation; (3) the volume is so small that its installation should not affect on the usage; (4) easy to be installed and maintained; (5) durable; (6) wireless, the installation and maintenance of large amount of signal cables are very difficult; (7) smart, which means individual or a set of individual sensors can process sensed data and directly outputs the information regarding the health/damage status of the structure; (8) anti-electromagnetic wave. Otherwise it is difficult to practically maintain such a huge number of sensors, and to process and obtain needed health information from a huge amount of sensed raw data. In addition to the cost, durability, and maintenance, the requirement of smart and wireless sensor is very important. So, a new type of modern structural health monitoring system is shown as figure 2.

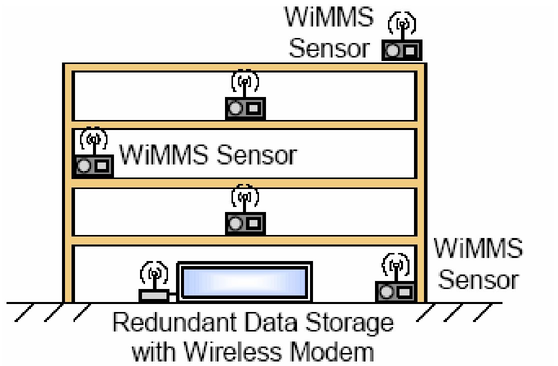

Fig. 2 Decentralized wireless structural monitoring systems (Cited from J.P. Lynch)

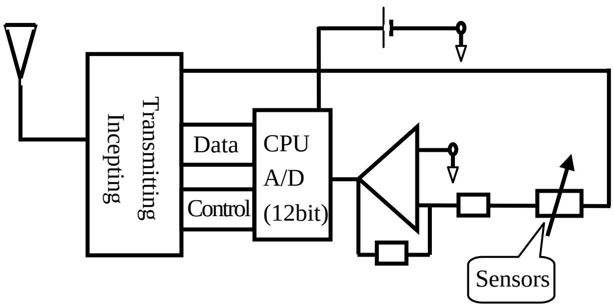

Fig. 3 framework of wireless transmission system

At the present time, the domestic studies that wireless monitoring system is applied to structural health diagnosis are very few. PEI Qiang, GUO Xun and ZHANG Min-zheng (2003) presented an idea of wireless monitoring system, and designed the framework of wireless transmission (figure 3). There were some results about wireless monitoring system in abroad. Erik Gregory Straser (1998) and Jerome Peter Lynch (2002) studied wireless structural damage diagnosis system. J.P. Lynch et al. (2003) presented wireless active sensor, they used 16-bit A/D converter and 32-bit CPU. J.P. Lynch et al. (2003, 2004a, 2004b) presented a model of wireless actuator and sensing unit including actuator, storage and signal transmission module.

Wireless data acquisition system designed by the authors is made up of data acquisition unit, data storage unit, wireless transmitting-incepting control unit, data transportation and computer communication unit altogether four parts. The working process of wireless data acquisition system is following. Firstly, data acquisition unit sends the signal of the vibration transducer modulated and A/D converted to CPU control unit, and then CPU control unit storages the data according to some logic relation. Secondly, the adaptive data are sent out wirelessly by wireless transmitting device, and then the data transmitted are received by wireless incepting device. At the same time, the data are sent to computer through the serial port.

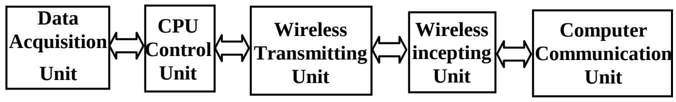

Fig. 4 The framework of wireless data acquisition system

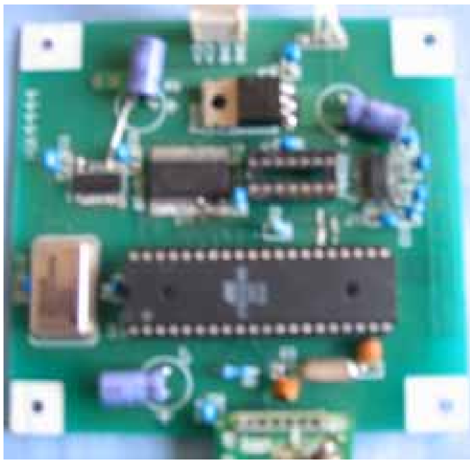

Fig. 5 top view of finished prototype wireless sensing unit

3.1 *Components and Working Principle of the Wireless System*

The wireless transmitting system is intended to 1) collect measurement data from sensors installed on the structural element, 2) storage, manage and locally process the measurement data collected, and 3) to communicate data and results to a computer. To accomplish the above operational functions, the framework of wireless data acquisition system is divided into five parts as shown in figure 4: Data Acquisition Unit, CPU Control Unit, Wireless Transmitting Unit, Wireless Incepting Unit and Computer Communication Unit. Fig. 5 shows a picture of the completed prototype wireless sensing unit. The printed circuit board is packaged at the top of the unit with the wireless modem housed beneath.

3.1.1 *Data Acquisition Unit*

The function of data acquisition unit is collecting the vibration signals of the sensors, its working process is following, firstly, the analog signals of vibration sensors is sent to A/D converter by low-pass filtering and signal amplifying and modulating, here, the A/D converter is a 12-bit analog-to-digital high speed A/D converter- LTC1410 produced by Linear Company. Secondly, for the conversion of analog sensor readings to digital forms, the 12-bit data signal converted by A/D is sent to a CPU control unit, and from the interface, the sampling frequency can be set as high as 100 kHz. The principle framework of data acquisition unit is shown in figure 6.

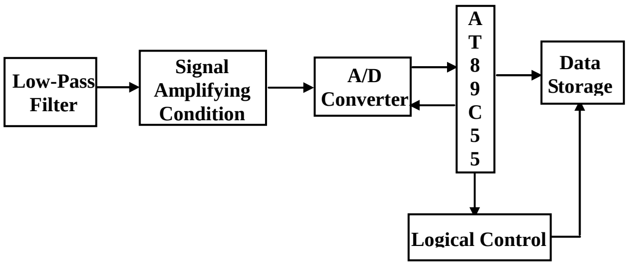

Fig. 6 The principle framework of data acquisition unit

3.1.2 *CPU Control Unit*

The core of the wireless sensing unit contains the computational power necessary for unit operation and for execution of embedded analyses. This is CPU control unit. The functions of CPU control unit are realizing to control A/D converter, data storage and wireless transmitting device with AT89C55, then, according to stated logic relation realizing data acquisition and wireless data transmitting-incepting using the program of single chip computer. The program of single chip computer is programmed by C51, as enhancing the practical application of the program and improving control precision.

3.1.3 *Wireless Transmitting-receiving Unit*

NRF401 chip with single-chip and wireless transmitting-incepting produced by NORDIC Company is selected to design the wireless transmitting-incepting unit, adopting well-rounded module. The functions and the circuit design of the nRF401 chip are introduced in detail as follows.

(1) The Functions of nRF401 chip

NRF401 is a true single chip UHF transceiver designed to operate in the 433MHz ISM (Industrial, Scientific and Medical) frequency band. It features Frequency Shift Keying (FSK) modulation and demodulation capability. It has a high ability of anti-jamming. NRF401 operates at bit rates Up to 20kbit/s. Transmit power can be adjusted to a maximum of 10dBm. The sensitivity is high to –105 dBm. Working voltage is low to 2.7V. Power consumption is low, while incept waiting current is only 8 uA. Antenna Interface is differential and suited for low cost PCB antennas. NRF401 features a Standby mode which makes power saving easy and efficient. NRF401 operates from a Single +3-5V DC supply. As a primary application, nRF401 is intended for UHF radio equipment in compliance with the European Telecommunication Standard Institute (ETSI) specification.

(2) nRF401 Chip Circuit Design

The inner circuit of the chip is shown in figure 7.

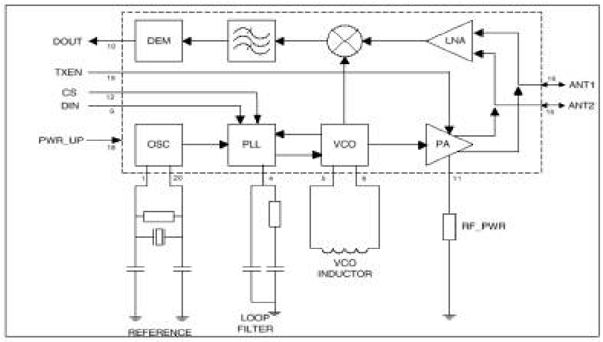

Fig. 7 inner circuit of nRF401

(3) The Electric Features of nRF401 Chip

The electric performance of the nRF401 chip is shown in table 1.

Table 1 Summary of nRF401 Chip Electric Features

Parameter	Target Index	Remark
Frequency Channel1/Channel 2	433.92MHz/434.33MHz	
Modulation Mode	FSK	
Maximum Output Power	10dBm	@400Ω 3V
Incepting Sensitivity	-105dBm	@400Ω BR=20kbit/s
Working Voltage	2.7～5.25V	
Incepting Supply Current	10mA	
Transmitting Supply Current	8mA～30mA	
Standby Supply Current	8uA	
Parameter	Target Index	Remark
Frequency Channel1/Channel 2	433.92MHz/434.33MHz	
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(4) Electro-circuit Design

NRF401 chip considers convenience of user's programming and using, for example, NRF401 can be connected to the serial port of single-chip computer while transmitting and incepting data directly, no needs to make data do the Manchester coding. Other transmitting-incepting single-chip RF only transmits the Manchester coding data. Using Manchester coding, the complexities of programming enhances, data transmission is deficient. The practical speed is only half of the standard speed, it doesn't meet the request of real-time transmission. Now, NRF401 is one of the RF transmitting and incepting chip that possesses the least outer components, it is very friendly for users. For example, adopting 4MHz crystal oscillator being easy to get, the cost is decreased very remarkably and the activity is improved.

According to the requests of nRF401 chip, in design the application circuit recommended is adopted, transmitting and incepting ports of nRF401 are connected to the serial port of the single-chip computer, and then a transmitting-incepting control antenna is come into being from the single-chip computer. The circuit design principle of nRF401 is shown in figure 8.

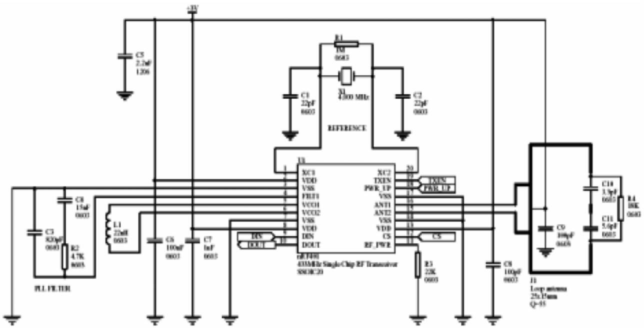

Fig. 8 circuit design principle of nRF401 chip

3.2 *The framework of wireless transmitting-receiving unit communicating with computer*

Communication between wireless transmitting-incepting device and computer is realized as following steps (see figure 9). The central control unit-CPU incepts available data reserved by data acquisition unit through wireless transmitting-incepting device, at the same time, available data are sent to upper computer by using the serial port of the computer.

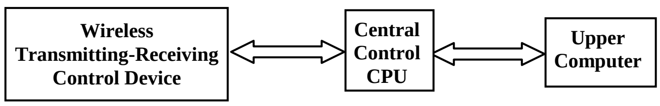

Fig. 9 Communication framework between Wireless Transmitting-Receiving unit and Computer

3.3 *Technique target of wireless transmission system*

The initial aims of the wireless transmission system in this paper are measuring the signal below the girder from on the top of the girder. The material operations are shown as following. Firstly, the transmitting device and relevant transducers are installed on some member of the bridge below the bridge girder. Secondly, we bring the incepting device walking along on the top of the girder and command the device to incept signal from the transmitting device while locating above the transmitting device and transducers. So the transportation distance is relatively short. But other aim-parameters are very advanced. All the technique targets of the wireless transmission system are shown as following in total 12 aspects.

1) Transportation distance: 15m~20m
2) A/D resolution: 12-bit
3) A/D converting rate: 1.25Msps
4) Memory capability: 32K
5) Storage time: 30s
6) Input resistance: >500KΩ
7) Supplying voltage: ±12V
8) Device power consumption: 200mW
9) Sampling frequency: 500Hz
10) Usage temperature: -30℃~60℃
11) Signal input scope: ±5V;
12) Low-pass filtering frequency: 150Hz

4 VALIDATION VERIFICATION

Fig. 10 Photo of Two-story Steel Frame Structure Model

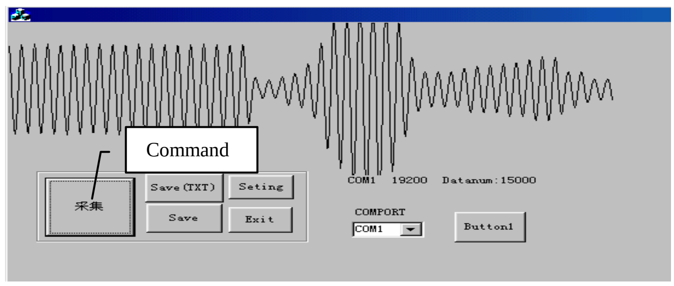

Fig. 11 Test Signal and Interface of Wireless Transmission System

The wireless health monitoring system explored in this paper was verified through a one-bay and two-story steel frame structure model (see figure 10). The aim of the experiment is to verify the reliability of the signal receiving from the wireless system. So, two types of sensors had been installed on the second floor of the model. One is cable-based sensor, the other is wireless sensor. Test signal and interface of wireless transmission system is shown as in figure 11. The signal appeared in figure 11 was generated by a signal generator, including three types of signals. The first section was a stationary and undamped signal, and then the amplitude of the signal was increased abruptly, and the frequency of the increased-amplitude signal was changed. This variable process was transmitted to computer and recorded by the wireless system.

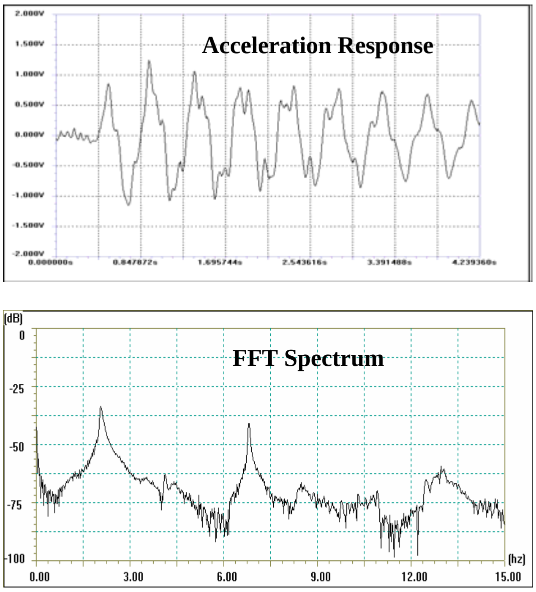

Fig. 12 the Acceleration Response (Up) and Corresponding FFT Spectrum (Down)the Data was Obtained Wirelessly

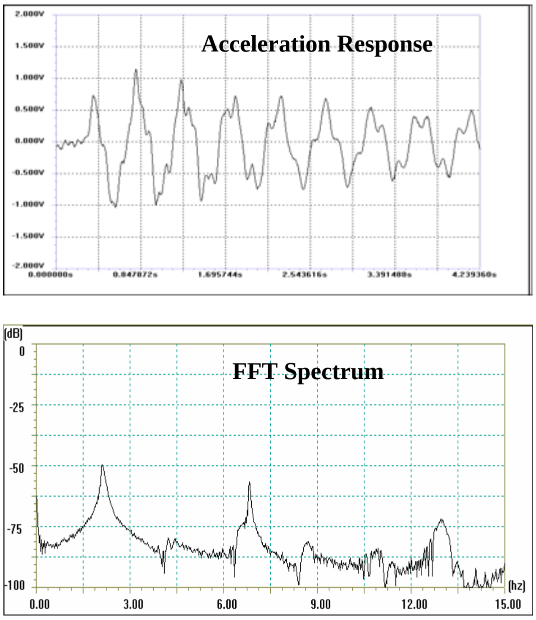

Fig. 13 the Acceleration Response (Up) and Corresponding FFT Spectrum (Down)the Data was Obtained with Wire-based Sensor

In the experiment, the wireless transmitting-incepting system will be responsible for commanding to receive valid data from the sensors installed on the model. And then, the data are sent to the computer through the serial port transferring wire. Lastly, we can analyze the data using corresponding program on the computer. According to the analyzing results, structural modal parameters can be identified. The acceleration response (Up) and corresponding FFT spectrum (Down) are shown in figure 12 and figure 13. The data in the former figure was obtained wirelessly. And the data in the latter figure was obtained with wire-based sensor. From results of these two figures, the signals of the two types of sensors are almost identical. After comparing the time-domain signal, the frequency-domain signal processed by FFT is also compared. And the two orders modal frequencies are also identical.

5 CONCLUSION REMARKS

To reduce installation costs and improve functions of health monitoring, new technologies are currently adopted in structural health monitoring systems. This study has explored the feasible schemes to overcome this disadvantage. And that is capable of greatly reducing the installation costs. The proposed wireless structural health monitoring system is capable of recording and receiving the response measurements correctly. Hence, signal transferring cables are no longer required in practical measurements. To illustrate the reliability and advanced performance of the wireless structural health monitoring system, an experimental study of modal parameter identification of one-bay and two-story steel frame structure model is employed. With the impulse excitations, the structural model responses are measured by wired and wireless system respectively. Comparing the two response measurements, it is very identical. This simple but nontrivial experiment has verified that the system is reliable and accurate.

Future improvements can be made to the current wireless sensing unit design. Immediately evident was a need for improved A/D converter resolution and increased memory for the storage of temporary measurement data. As the embedded system market evolves, new and innovative technologies that emerge should be considered for inclusion in the wireless sensing unit to broaden its capabilities while reducing costs. With respect to embedded application software, more work is needed to explore the integration of data interrogation schemes such as those that perform damage detection analysis.

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