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# Design, calibration and application of wireless sensors for structural global and local monitoring of civil infrastructures

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**Abstract.** Structural Health Monitoring (SHM) gradually becomes a technique for ensuring the health and safety of civil infrastructures and is also an important approach for the research of the damage accumulation and disaster evolving characteristics of civil infrastructures. It is attracting prodigious research interests and the active development interests of scientists and engineers because a great number of civil infrastructures are planned and built every year in mainland China. In a SHM system the sheer number of accompanying wires, fiber optic cables, and other physical transmission medium is usually prohibitive, particularly for such structures as offshore platforms and long-span structures. Fortunately, with recent advances in technologies in sensing, wireless communication, and micro electro mechanical systems (MEMS), wireless sensor technique has been developing rapidly and is being used gradually in the SHM of civil engineering structures. In this paper, some recent advances in the research, development, and implementation of wireless sensors for the SHM of civil infrastructures in mainland China, especially in Dalian University of Technology (DUT) and Harbin Institute of Technology (HIT), are introduced. Firstly, a kind of wireless digital acceleration sensors for structural global monitoring is designed and validated in an offshore structure model. Secondly, wireless inclination sensor systems based on Frequency-hopping techniques are developed and applied successfully to swing monitoring of large-scale hook structures. Thirdly, wireless acquisition systems integrating with different sensing materials, such as Polyvinylidene Fluoride(PVDF), strain gauge, piezoresistive stress/strain sensors fabricated by using the nickel powder-filled cement-based composite, are proposed for structural local monitoring, and validating the characteristics of the above materials. Finally, solutions to the key problem of finite energy for wireless sensors networks are discussed, with future works also being introduced, for example, the wireless sensor networks powered by corrosion signal for corrosion monitoring and rapid diagnosis for large structures.

**Keywords:** wireless sensor network; structural health monitoring; civil infrastructure; energy optimization; wireless digital acceleration sensor; wireless inclination sensor; MEMS; PVDF; cement-based sensor.

## 1. Introduction

Civil engineering structures suffer from damages caused by environmental loads, fatigue, caustic effect and material aging, thus, their strength is reduced inevitably during their service time (Ou and Guan 1999). In order to assess these damages and make appropriate decisions to keep the structures in good service, it is essential to implement a damage detection strategy, this process is referred to as

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structural health monitoring, which is divided into global and local monitoring (Housner *et al.* 1997). One important element in a SHM system is the transmission of the measurement data from the sensors to the processing terminal, and wired networks are used for this task conventionally and most popularly. The wired sensors have many advantages: they transmit data with high fidelity, the products of wired sensors are mature, and they are inexpensive with a plenty of choices. However, with a great number of sensors for a large structure, a huge amount of wires is needed. As a result, installation time and costs can be very high, and this may also affect the reliability of the data transmission and increase the maintenance cost. Moreover, there may be cases in which wires cannot be placed in certain locations of a structure or even in the entire structure. Fortunately, with the development of technologies in sensing, wireless communication, and micro electro mechanical systems (MEMS), wireless sensor network technique has been developing rapidly, and is being used gradually in SHM for civil engineering structures for reducing the high capital costs associated with wire-based structural monitoring systems (Spencer 2003a).

Some of the first efforts in developing wireless sensors for applications to civil infrastructures were presented by Straser and Kiremidjian (1996) and Straser *et al.* (1998). Based on the above work, Lynch *et al.* demonstrated a proof-of-concept wireless sensor that uses standard integrated circuit components, and the sensor unit has been validated through various experiments in the laboratory (Lynch *et al*. 2001, 2003). Maser *et al*. (2003) proposed the Wireless Global Bridge Evaluation and Monitoring System to monitor the condition and performance of bridges remotely. Brooks (1999) emphasized the necessity of migrating some of the computational processing to the sensor board, calling them "Fourth-generation sensors". Mitchell *et al*. (1999) presented a wireless data acquisition system for health monitoring of smart structures, and Mitchell *et al*. (1999) continued this work to extend cellular communication between the central cluster and the web server, allowing web-control of the network. Liu *et al.* (2001) presented a wireless sensor system that includes five monitoring stations. Ou and Li (2003) presented a wireless sensor network for the health monitoring of offshore platforms, and developed a laboratory prototype to demonstrate the feasibility of the proposed network. Yu *et al.* (2004), Shiraishi *et al.* (2005) and Glaser *et al.* (2007) presented more models of wireless sensor networks. Moreover, in 2000, the "Smart Dust" project was funded by the US Defence Advanced Research Projects Agency (DARPA). In this project, the ultimate goal was to develop a low-cost, small, and highly reliable wireless sensing system (Spencer 2003b). Now this system is now widely being used in theoretical research and practical applications.

In this paper, some recent advances in research, development and implementation of wireless sensors for the SHM of civil infrastructures in DUT and HIT in mainland China, are introduced. The main contents include wireless digital acceleration sensors for structural global monitoring; wireless inclination sensors systems based on Frequency-Hopping; wireless acquisition systems with different sensing material proposed for structural local monitoring.

## 2. Wireless digital acceleration sensors for structural global monitoring

### 2.1 Design of wireless digital acceleration sensor

On the basis of existing MEMS and embedded techniques, a wireless digital acceleration sensor is constructed by integrating several modules that include: a detection unit, a microprocessor unit, a wireless transceiver and a power unit.

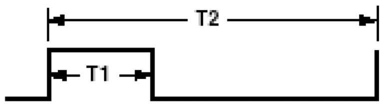



Fig. 1 Duty cycle modulated

The detection unit consists of an accelerometer and a temperature meter. For the first, a good choice is the ADXL202, a low-cost, low-power, and complete 2-axis accelerometer. It has a surface micromachined polysilicon structure built on top of a silicon wafer. A pin is available on each channel to allow the user to set the signal bandwidth of the device by adding a capacitor. This filtering improves the measurement resolution and helps to prevent aliasing. After being low-pass filtered, the analog signal is converted to a duty cycle modulated(DCM) signal, which can be decoded with a counter/timer or with a low cost microcontroller. The DCM period is shown in Fig. 1, where T1 is Length of the "on" portion of the cycle and T2 is length of the total cycle.

The acceleration can then be determined by

$$a = \frac{T_1/T_2 - u_{0g}}{u_{1g}} = \frac{T_1 - T_{10g}}{T_{1g}} \tag{1}$$

where

$$u_{0g} = \frac{T_{10g}}{T_2}, \quad u_{1g} = \frac{T_{1g}}{T_2} \tag{2}$$

and $T_1$ is the measured value of the DCM output, $T_{10g}$ is the DCM output at zero acceleration, $T_{1g}$ is the DCM output at 1g acceleration, and $T_2$ is the period of the DCM output. Although the typical value for $u_{0g}$ is 0.5 and the one for $u_{1g}$ is 0.125, both $T_{10g}$ and $T_{1g}$ are required to be calibrated according to the temperature before application. For $T_{10g}$ and $T_{1g}$ in Eq. (1), the theoretical values can be found from the specifications of the ADXL202 product. However, these values are temperature dependent, and must be revised based on a table stored in $E^2$PROM of the microprocessor. According to the measured temperature, $T_{10g}$ and $T_{1g}$ are selected from the table, and then the acceleration value can be obtained from Eq. (1) based on the measured $T_1$. Since most civil engineering structures have low natural frequencies, a bandwidth of 50 Hz will be sufficient for measuring their dynamic responses in practical applications. The noise level is 1.8 mg which is usually much lower than the amplitude of the signals. $T_2$ is designed to be 1ms, i.e., the DCM frequency is 1000 Hz. This will meet the requirement that the frequencies of the analog signals are less than 1/10 of the DCM frequency.

For the temperature meter, the TC1047 chip with low power consumption and a low power voltage between 2.7 V and 4.4 V is used. One advantage of the TC1047 is its linear relationship between the voltage output and the measured temperature. The typical slope of the voltage output vs. the temperature is 10 mV/$^o$C, and the temperature measurement ranges from -40 $^o$C to +125 $^o$C. The TC1047 is in a small 3-Pin SOT-23B package, making it an ideal choice for space critical applications.

The microprocessor unit used in this design is the Atmega8l chip, which integrates a large storage memory and interface circuits. As a microprocessor with low cost, the chip adopts a small pin package. Its main features are as follows: 8 bit high performance, low cost AVR micro-controller with advanced RISC simplified instruction aggregation structure, a number of powerful external interface circuits, and five sleep modes including idle, ADC noise reduction, power-save, power-down and standby. As a processing unit for the wireless sensor, the Atmega8l could gather, pre-process the analog and digital output from the detection unit. And it could also exchange data with the wireless transceiver.

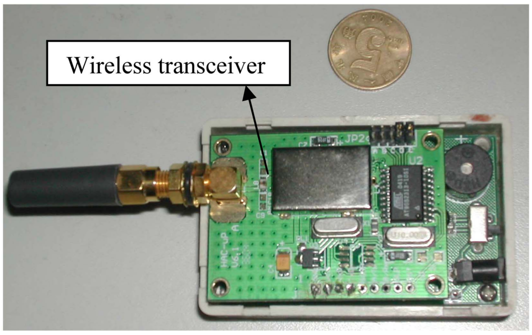



Fig. 2 Wireless digital sensor

Wireless transceiver is used to transmit data collected by sensors to base station. In this research, wireless transceiver is developed on the basis of CC1020 radio frequency chip produced by Texas Instrument Corporation, which is a true single-chip ultra RF transceiver with high frequency and low power. The CC1020 circuit is mainly intended for the ISM(Industrial, Scientific and Medical) and Short Range Device frequency bands. Besides, CC1020 data rate is up to 153.6 kBaud. The CC1020 wireless transceiver is steady and its transmission distance is up to 500 meters.

For a wireless sensor, energy is usually provided through solar power (Kohvakka *et al.* 2003), structural vibration (Scott *et al.* 2001), chemical batteries or lithium batteries. In the present design, lithium batteries with charge circuits are used, taking into account their small volume and relatively long service time. The above units are integrated into a wireless digital acceleration sensor node. In addition to measuring the acceleration and the temperature, the wireless sensor also sets a limit for the acceleration and performs the alarm function using a buzzer. A computer connected with a wireless transceiver is a base station. The wireless digital sensor node is shown in Fig. 2, the wireless transceiver is in the upside of the node, and the detection unit and microprocessor unit are integrated into a printed circuit board which is put under the node.

The lithium battery used in the design has the specifications of 900 mAh and 3.6 V. It supplies power to the entire wireless sensor node. The current in the wireless sensor is 14.7 mA while it is collecting and transmitting data, and the sensor node could work for about 61 hours in this mode. When a wireless sensor is idle, its current is 152.5 $\mu$A, and the battery life is as long as about 246 days.

### 2.2 Calibration

The acceleration of the designed wireless digital sensor was tested using the device shown in Fig. 3. It is a servo-mechanism system consisting of an electromotor and a track for movement. The electromotor may move on the track back and forth to produce a periodic acceleration wave. In the test, the electromotor moves periodically with a frequency of 1 Hz.

A wireless sensor is put on the electromotor to measure the acceleration. For comparison purposes, a wired sensor is used as the reference sensor. The time histories of the reference and measured acceleration waves are depicted in Fig. 4. There exit minor differences because the wireless sensor with no encapsulation is possibly disturbed and its sample rate is low, but they match well generally. Fig. 5(a) and (b) show the power spectral density of the two acceleration processes, respectively. The peak frequency of the measured acceleration is 0.9825 Hz, while that of the reference acceleration is 0.9985 Hz. Such a small difference meets the requirement for the

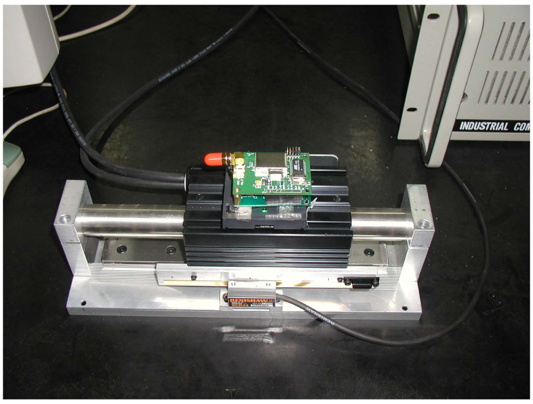


Fig. 3 A picture of the acceleration testing device

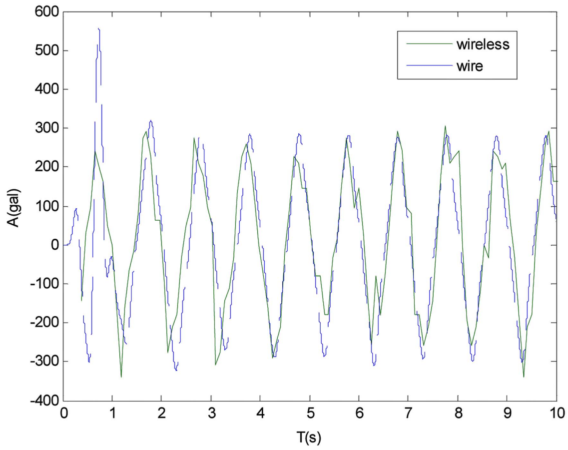
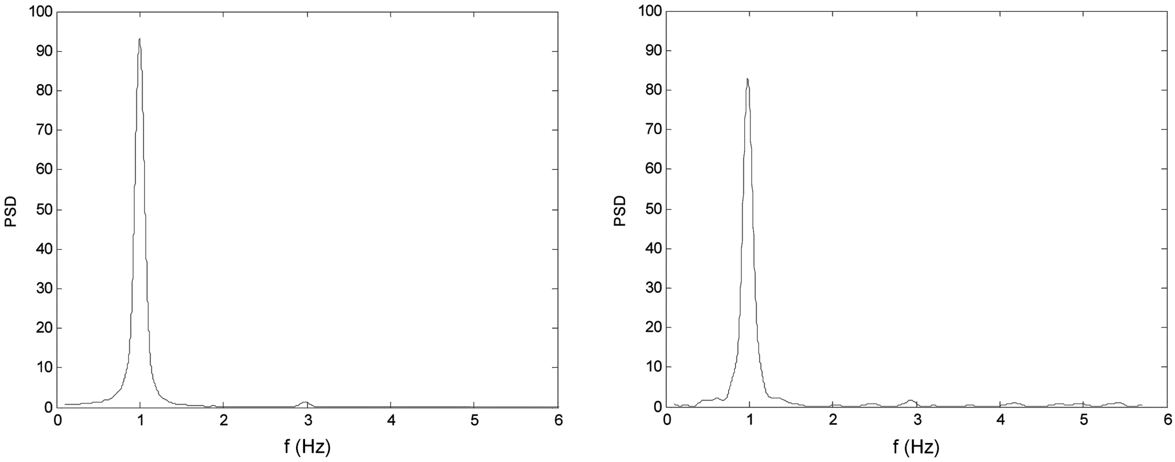



Fig. 4 Time histories of acceleration waves




(a) Reference acceleration

(b) Measured acceleration

Fig. 5 Power spectra of acceleration processes

SHM in civil engineering.

### 2.3 Application: wireless sensors experimental system for ice-induced vibration monitoring of an offshore platform model

The wireless sensor test is finished on the offshore platform model of Bo Sea JZ20-2MUQ. The scale factor between the experimental model and the true offshore platform is 1/10. The model and its actual dimension are presented in Fig. 6. A wireless sensing test is performed to monitor the vibration of this model in different push ice and bend ice, with two wireless sensor nodes put respectively on the elevation height locations of 2.5 meters (node 1) and 2.85 (node 2) meters of this model. Wired acceleration sensors are also put in the corresponding place. The location of the ice loading is selected at the elevation height of 0.4 meters relative to the ground, which means that the location is corresponding to the ice loading of the practical offshore platform.

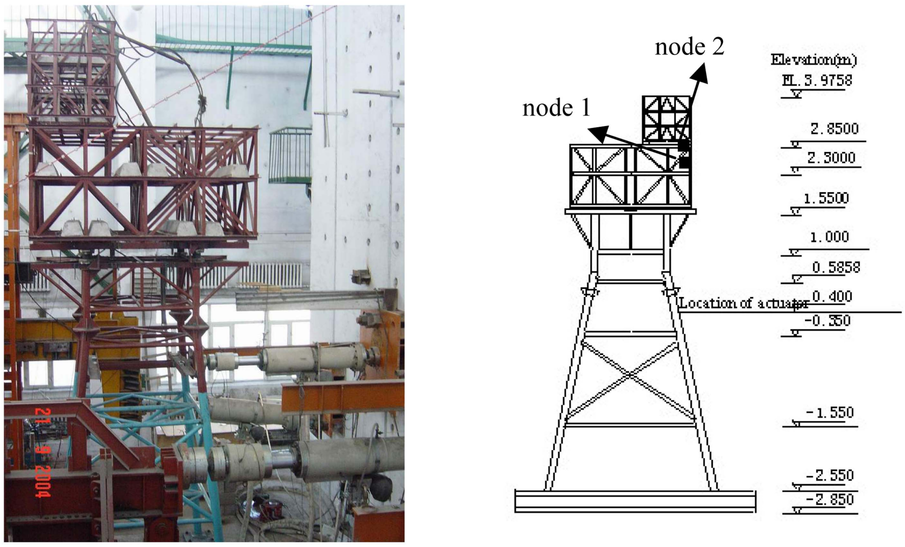



Fig. 6 Offshore platform module and its height

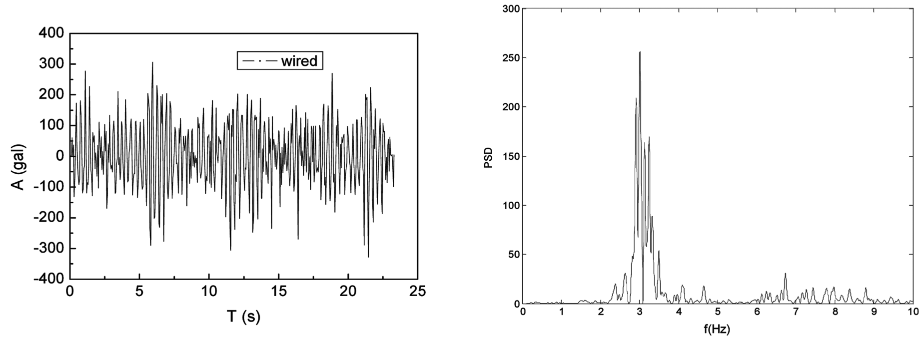
Two wireless sensor nodes and a base station composed of a wireless sensor network used for the structural health monitoring of offshore platform. The time histories and the power spectral density of the two wireless acceleration sensors and corresponding wired sensors are depicted in Fig. 7. Although minor differences are present in time histories, they agree relatively well. For the power spectral density: for Figs. 7(a) and (b), the peak frequency of the measured acceleration is 3.0127 Hz, while that of the reference acceleration is 3.1154 Hz; for Figs. 7(c) and (d), the peak frequency of the measured acceleration is 3.0064 Hz, while that of the reference acceleration is 3.1299 Hz.

## 3. Wireless inclination sensors systems based on frequency hopping technique for swing monitoring of large-scale hook structures

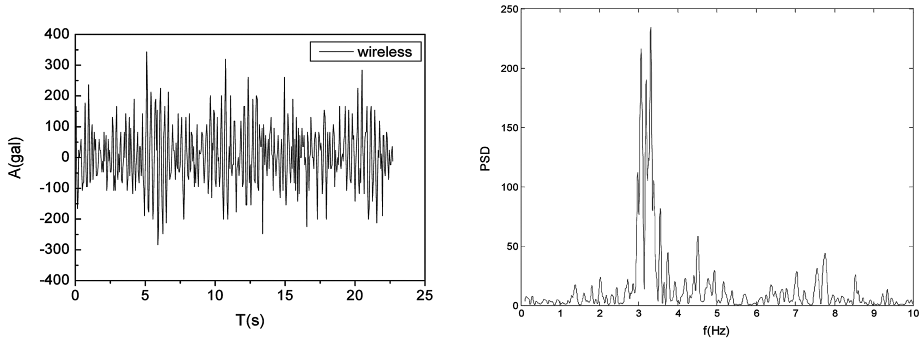
Large Scale Heavy Derrick Lay Barge is very important for sea work. Under intense wind and wave load, the hook on the barge will vibrate so large that it can not function in some cases. Through installing the Tuned Mass Damper (TMD) on the hook, the vibration will be reduced to an acceptable range to meet the demand on sea work, which is also important for increasing the efficiency of the sea work (Ou *et al.* 2006). To design the suitable TMD for the hook, the dynamical parameters should be specified beforehand, the related dynamical parameters such as the inclination and the acceleration are measured by wired sensors. However, due to the restrictions of the reality, the wired sensors are very hard to implement. Thus, wireless sensors have been presented to overcome the shortcomings of these wired ones. It is more suitable and also more convenient to utilize wireless sensors to acquire the useful data of large scale heavy derrick lay barge.

### *3.1 Wireless inclination sensors systems structure*

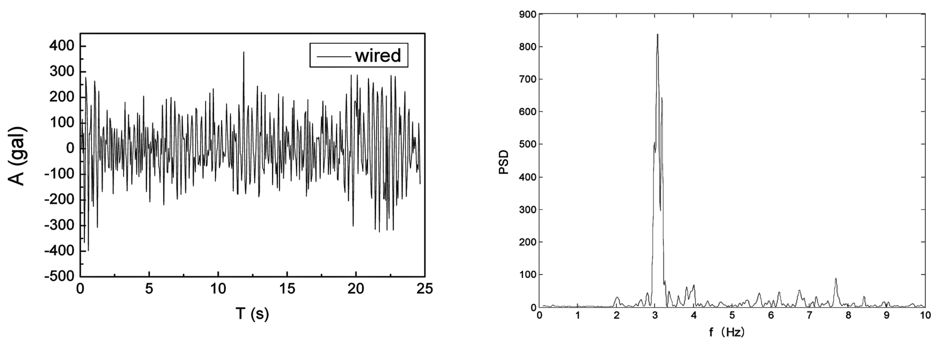
Frequency-Hopping is one of the basic modulation techniques in wireless communication. It changes



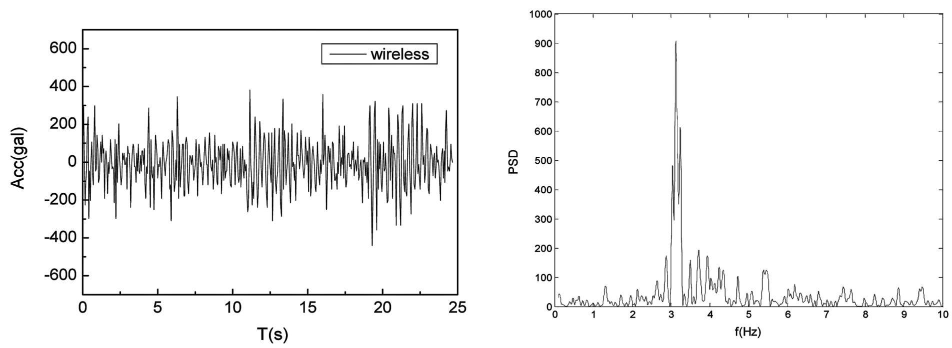

(a) Reference acceleration wave of node 1




(b) Measured acceleration wave of node 1




(c) Reference acceleration wave of node 2




(d) Measured acceleration wave of node 2

Fig. 7 Graphics of acceleration collected by wireless and wired sensors network in an operating mode carried frequency through and through for reliable signals transmission. The rate of Frequency-Hopping reflects the performance of the system: the faster Frequency-Hopping is, the better the performance we can get. The rate is up to ten thousands times a second in military communication, while the rate is about 50 times a second for commercial communication. Low rate wireless local area networks adopt slow Frequency-Hopping because of its easy implementation. Based on this idea, wireless inclination sensors systems with multi-frequency channels are proposed. Every wireless sensor has different communication channels, and base station have multiple communication channels covered with the wireless sensors' ones. In this way, the base station can communicate with all nodes in separate channels using simple protocol.

Using recent developments in existing MEMS and wireless communication, the data transmission structure of wireless inclination sensors systems is as follow (Yu *et al.* 2009). The inclination data sensed by inclinometer MEMS chip is processed and transformed into serial data. Using the wireless communication module with a single special frequency channel, the serial data is transmitted to a wireless base station with multi-frequency channels. The status of the structure can be estimated by the method of diagnosis arithmetic based on the collected data.

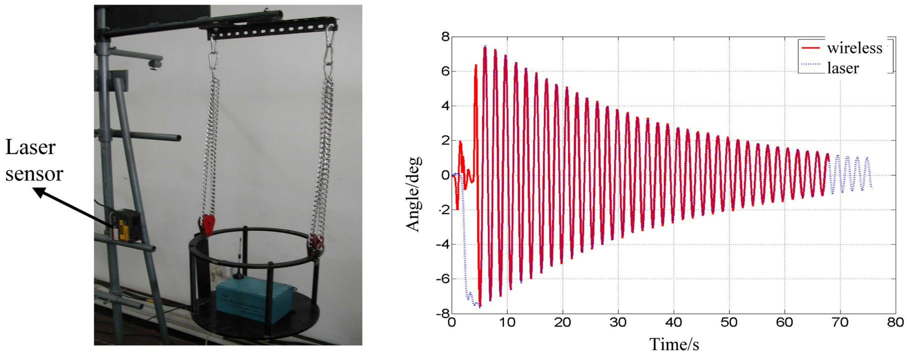
### *3.2 Wireless inclination sensor*

In this system, the wireless inclination sensor is integrated using a sensing disposal unit, a wireless communication unit and a power unit. A sensing disposal unit, consisting of an inclinometer chip and micro-processing unit circuits, can measure the swing and transform these data into a serial form for future transmission. The SCA100T chip, which is low-cost, low-power chip with 3D-MEMS-based dual axis, is selected in this design for swing monitoring. And the temperature compensation using the internal temperature sensor makes the inclination measure more precise. Connected with SPI of SCTA100T, the micro-processing unit can read and pre-process the inclination data, then transmit the data to wireless transceiver by using the RS485 signal format. In the present design, two groups of lithium batteries with charge circuits are being used as power units, taking into account their small volume and relatively long service time. One of the batteries outputs 5 V for wireless communication unit while the other one outputs 12 V for the sensing disposal unit. The integrated wireless inclination sensor and the base station are shown in Fig. 8. The sensing disposal unit and the power unit are put under the designed box. A wireless communication unit is deployed with a high-gain antenna outside the box to transmit data for farther distance.

### *3.3 Calibration*

The calibration experiment is performed in a pendular experimental equipment shown in Fig. 9(a).


Fig. 8 Wireless inclination sensor and base station




(a) Experimental equipments (b) result

Fig. 9 Experiment of calibrating wireless inclination sensor

The wireless inclination sensor is put in the structure and a laser displacement sensor is used for measuring the structures' displacement as a reference. For the laser displacement sensor, the relation between measuring displacement Δ and real swing angle $L$ is expressed in the following Eq. (3)

$$\sin\alpha = \frac{\Delta}{L} \tag{3}$$

where $L$ is pendulum length. In this experiment, the pendulum length is about 91.97 cm, the pendular cycle is 1.9055s, and the wireless measure data and laser sensor's angle are acquired by the designed data acquisition system. The experimental results are shown in Fig. 9(b). The maximal error is about 1% by analysis for the wireless inclination sensor while the laser sensor is used as a reference, this may meet the swing monitoring requirements. The wireless sensor node's measuring range is ±30$^{o}$, and the frequency response is more than 20 Hz.

### *3.4 Application: wireless acquisition system experiment for swing monitoring of large scale Heavy Derrick Lay Barge's hook model*

As an ocean engineering boat, Lanjiang Heavy Derrick Lay Barge with main and assistant hooks has the strongest lifting capacity in Asia and can lay pipes in the seabed (shown in Fig. 10). Its sea work ability is the first in Asia and the sixth in the world. It can work at 150 meters below water and it can

Fig. 10 Heavy Derrick Lay Barge of Lanjiang

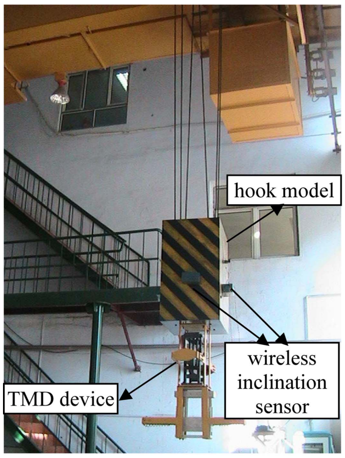



Fig. 11 The actual hook structural model and experimental system

also lift up to 3800 tons. However, the hook on the barge vibrates seriously in the case of intense wind and wave load. Sometimes it even fails to function properly and causes great economic lost. Thus, the hooks' swing must be monitored with a wireless inclination sensor system and controlled by the dampers. On the basis of practical applications, an innovative gear-pendulum-type TMD control system is proposed. This system is more robust than the single pendulum TMD control system, as it avoids the requirement that the length of the pendulum TMD and the control system must be the same.

To validate the proposed TMD system, we used wireless inclination sensor to monitor the swing of the hooks with control and without control. The bridge crane with a lifting capacity of 10 tons is reconstructed into hook model. The scale factor between the experimental model and the true hook is 1:4, the scale factor of mass is 1:64, the scale factor of time is 1:2 and the scale factor of inclination and acceleration is 1:1. The designed control system is loaded on the hook model to control the swing angle of hook. The hook is influenced by the loads of wind, ocean wave at the lowest level. The wireless inclination sensors are also put on the model to monitor the swing. The actual hook structural model and their experimental system are shown in Fig. 11.

In this experiment, inclination of the model is gathered by wireless sensors in the status of with-control and without-control. Fig. 12 shows a continuous test of wireless inclination data: in the same working condition, the structural damp with control is larger than the one without control and the swing range is less. This shows the control effect of the control module.

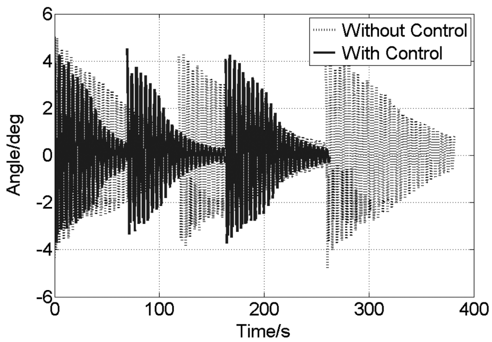



Fig. 12 Continuous test of obliquity with and without control

## 4. Development of wireless sensor nodes based on different sensing materials for structural local monitoring

Base on the above idea of a wireless inclination sensor system, wireless acquisition systems of some sensing materials sensors (as shown in Fig. 13) are designed for structural local monitoring. The Modulation circuit of this system, which changes signals of sensing material into a standard voltage signal, is different from various kinds of sensors. The processing unit with the A/D function adopts atmega8l, and wireless communication module is based on CC1020 chip.

### *4.1 Analysis of PVDF's characteristics using wireless acquisition system*

In recent decades, piezoelectric materials and devices are widely used in many technical areas (Kang *et al.* 1996). Among various piezoelectric polymers, PVDF film is well known for the advantages of good flexibility, strong corrosion resistance, low density, a few microns' minimum thickness, and a high piezoelectric voltage constant with small disturbance to the performance of the monitoring structure. By means of piezoelectric characteristics, PVDF film can be applied to shape control, vibration control and active damper fields in the flexible structure. Moreover, PVDF film shows excellent properties in the transmission of strain, acceleration and force parameters, with a relatively simple signal processing system and is easy to implement. Therefore, the sensing properties of PVDF have gradually attracted more attention (Ju *et al.* 2004). However, PVDF and its frequency response analysis used in the structural monitoring field are still at the exploratory stage, and can not form a complete and mature system for structural monitoring. Based on this, analysis of PVDF's characteristics used in civil strain monitoring and research of wired/wireless acquisition system are given as follows.

#### *4.1.1 Development of measurement circuit module*

Using PVDF's piezoelectric effect, strain measurement can be carried out. However, charge signals must be converted into voltage signals through charge amplifier. The PVDF sensing module is

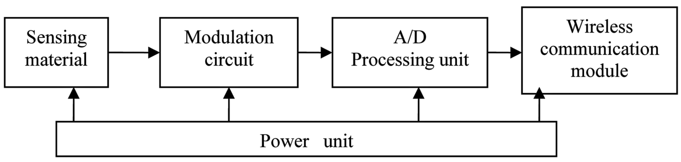



Fig. 13 Wireless acquisition systems of some sensing materials

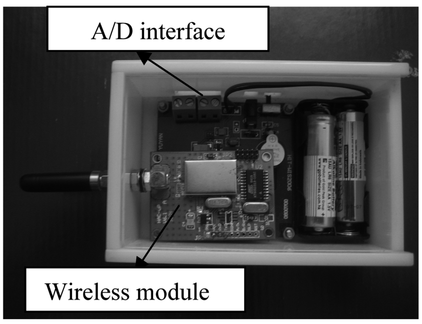



Fig. 14 Wireless acquisition module

designed for enlarging the change of PVDF charge, mainly made up of two operational amplifiers. The wireless acquisition module is shown in Fig. 14, the standard voltage signal is input into A/D interface, and then is collected and pre-processed by micro-processing unit for further wireless transmission.

#### *4.1.2 Experimental system and project*

The structure of the experimental system is shown in Fig. 15(a). The Agilent 33220 Digital Synthesis Function Generator is used to generate sinusoidal signals. The JZK-10 is a modal vibration exciter driven by power amplifier YE5872A for signal amplification, so that the beam with a constant strength begins to deform. PVDF sensor and resistance strain gauge are attached on the beam in the experimental system. Measured signals of beam deformation are converted into voltage signals and amplified respectively by the charge amplifier YE5850 and dynamic strain indicator YE3835. Then the amplified voltage signals are transmitted to the computer PC in wired or wireless mode to realize real-time data display, storage and analysis. Sensors layout is shown in Fig. 15(b).

As shown in the arrangement of sensors, the direction along the beam is known as the PVDF-0 and resistance strain gauge-0, while the direction perpendicular to the beam is known as PVDF-90 and resistance strain gauge-90. By using a number of sensors, vibration exciter loading tests on the beam were carried out to complete the following projects: comparing the response characteristics of the PVDF-0 and the resistance strain gauge-0; comparing the PVDF-0 and PVDF-90 to study the tensile direction of PVDF; analyzing the frequency characteristics of PVDF and resistance strain gauge, and exploring the appropriate strain measuring range of the PVDF and the resistance strain gauge.

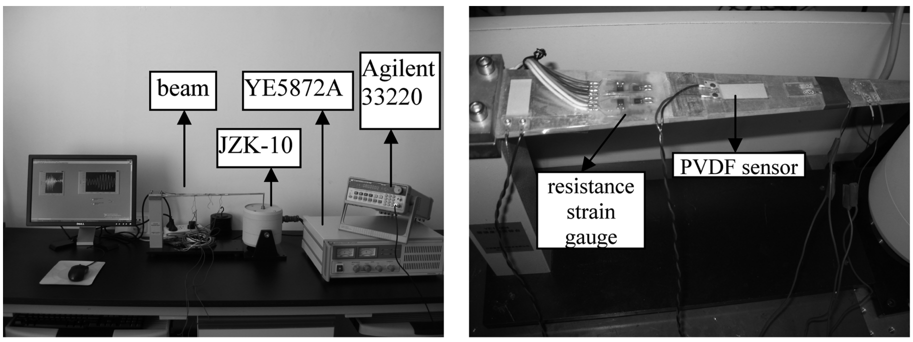
#### *4.1.3 Characteristics analysis*

##### *4.1.3.1 Vibration detection using PVDF-0 and the resistance strain gauge-0*

As shown in Fig. 16, in the same frequency, the output of PVDF film and resistance strain gauge show a linear relationship with the growth of drive signal. The actual measurement of PVDF film with the theoretical values calculated is shown in Fig. 17. The two curves show the same trend, but the measured value is smaller than the theoretical value as the actual leakage of charge.

##### *4.1.3.2 The effect of the tensile direction of PVDF film to the measurement*

Through loading drive of different amplitude on the beam, Fig. 18 uses the resistance strain gauge as




(a) Devices (b) Sensors layout

Fig. 15 Experimental facilities

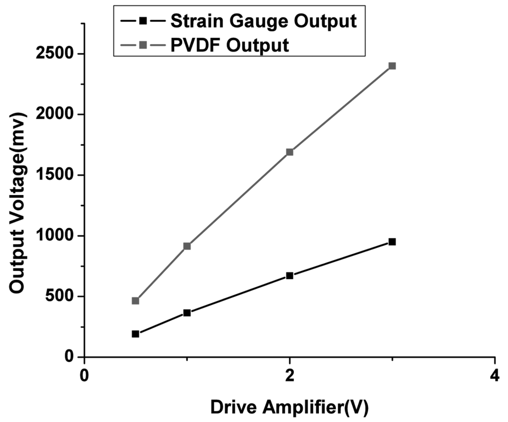


Fig. 16 Relationship between PVDF, resistance strain gauge and drive

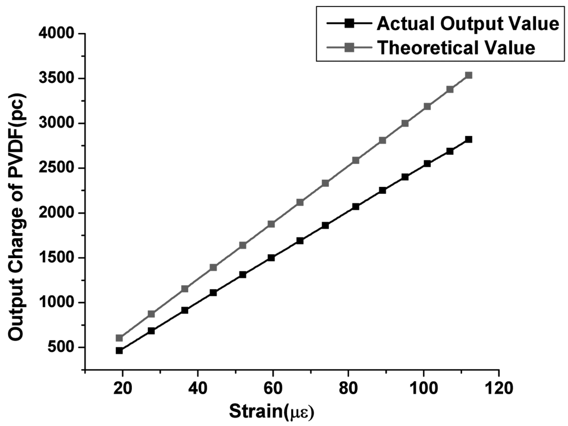


Fig. 17 Comparision of PVDF's theoretical values with the measured values

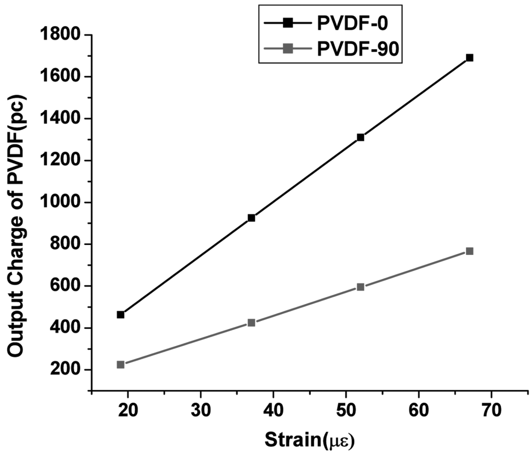


Fig. 18 comparison of PVDF output in different directions

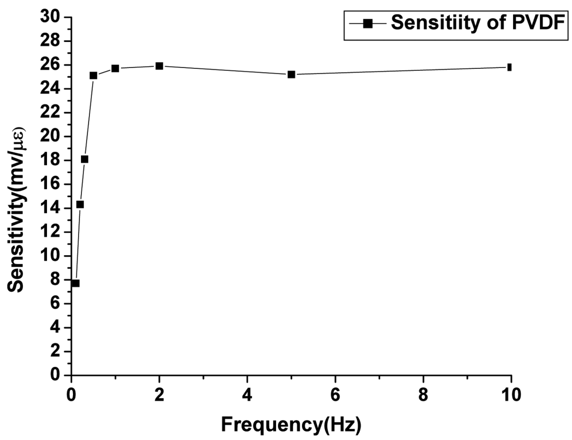


Fig. 19 Amplitude-frequency characteristic curve of PVDF

a standard to get corresponding curves of two PVDF's arrangement mode. It can be observed that PVDF tensile direction is preponderant direction, with different piezoelectric constant in different directions.

#### *4.1.3.3 Sensitivity experiment of PVDF*

To analyze and study the dynamic response of PVDF film, response signals of two sensors are collected in different frequencies. Through the processing of acquired signals, the dynamic sensitivity of PVDF sensors is calculated. PVDF' strain sensitivity is defined as the ratio of output voltage change caused by the strain change

$$S = \frac{\Delta V}{\Delta \varepsilon} \tag{4}$$

where $S$ is strain sensitivity, $\Delta V$ is voltage change, $\Delta \varepsilon$ is strain change. Under different excitation frequency (0.1 Hz-40 Hz), the amplitude-frequency characteristic curve of PVDF film is shown in Fig.


Fig. 20 Strain measuring system on concrete beam

19. The sensitivity is low under 0.5 Hz, but relatively stable around 0.5 Hz. PVDF film has high signal sensitivity during the dynamic strain measurement, and the higher the frequency, the more stable the performance of collecting strain.

### *4.2 Experiment of wireless strain sensor system on a typical concrete beam structure*

While using the strain gauge as a sensor and the bridge circuit as a modulation circuit (Yu and Ou 2009), there are mainly the circuits of amplification and filtering. As micro-changing signals are sampled in amplification, the instrument amplifier AD623 is selected. The two steps of Butterworth circuits are used for a filtering circuit. The signals of the civil engineering structures belong to low frequency ones, so the bandwidth within 20 Hz can already meet the requirement. Using the above modulation circuit, the change of the strain gauge could be output by a standard voltage signal.

The experiment of the wireless strain sensor system is finished on a typical concrete beam structure shown in Fig. 20. The strain gauge is affixed on a concrete beam, which could change regularly while the beam is loaded in rule. Furthermore, the change could be collected, disposed and transmitted wirelessly. In this test, the beam is loaded gradually up to the rate of 1000 kg. The measured data processed by using the data fusion method and the arithmetic average value method is compared and analyzed. In Fig. 21, results show that the wireless strain sensor can be installed easily and applied compatibly to local monitoring in civil engineering. The strain signal processed by the data fusion method is more accurate than the one processed by the arithmetic average value method. Thus, the proposed data fusion method is suitable for processing such slowly-changing signals as strain.

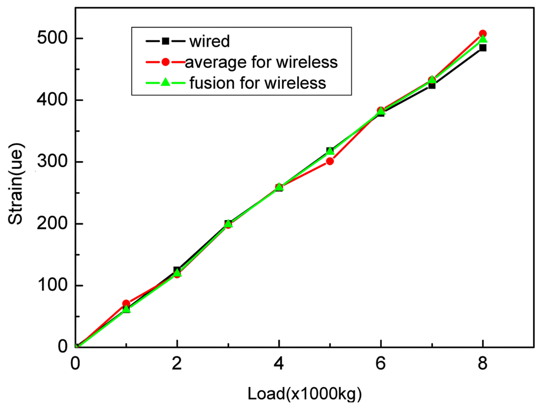



Fig. 21 Change between load and strain for wireless sensor and wired strain collection device

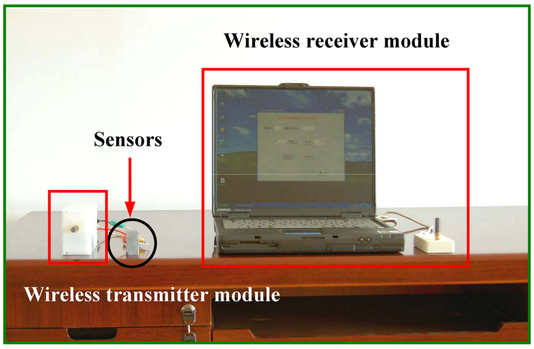
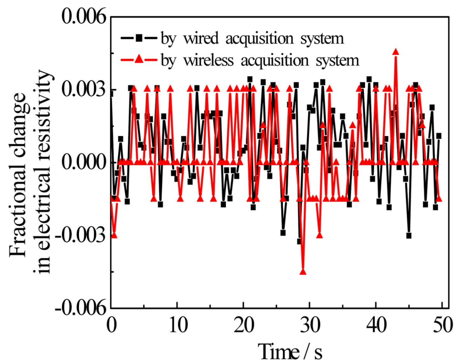


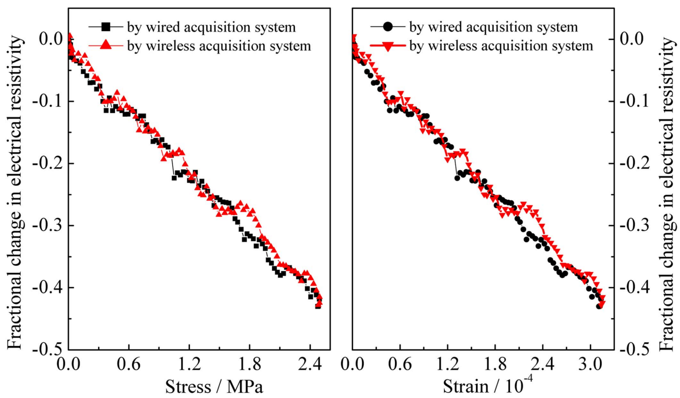

Fig. 22 Wireless acquisition system

### *4.3 Wireless stress/strain measurement system integrating with nickel powder-filled cement-based composite sensor*

A wireless stress/strain measurement system, shown in Fig. 22 (Han *et al.* 2008), is developed by integrating pressure-sensitive sensors for the health monitoring of concrete structures. The pressure-sensitive stress/strain sensors are fabricated by using nickel powder-filled cement-based composite and modulation circuits which adopt the direct-current four-electrode method to measure the fractional




(a) Without loading




(b) Under uniaxial compression

Fig. 23 Comparison of output signals by wired and wireless acquisition system change in electrical resistivity (i.e., the output signal) of the piezoresistive nickel powder-filled cement-based stress/strain sensors (Han *et al*. 2007, Ou and Han 2009).

The wireless stress/strain measurement system integrated with these sensors is tested with compressive stress/strain in the range from 0 MPa/0 $\mu\varepsilon$ to 2.5 MPa/311.5 $\mu\varepsilon$ for performance evaluation. Experimental results in Fig. 23 indicate that the electrical resistivity of pressure-sensitive nickel powder-filled cement-based stress/strain sensors decreases linearly and reversibly with the compressive stress/strain, and its fractional change goes up to 42.719% under uniaxial compression. The relationship between the input (compressive stress/strain) and the output (the fractional change in electrical resistivity) of the wireless stress/strain measurement system integrated with pressure-sensitive sensors is $\Delta\rho = -0.16894\sigma / \Delta\rho = -1336.5\varepsilon$. The wireless stress/strain measurement system can be used to achieve a sensitivity of stress/strain of 16.894% $MPa^{-1}$/0.13365%$\mu\varepsilon^{-1}$ (a gauge factor of 1336.5) and a stress/strain resolution of 150 Pa/0.02$\mu\varepsilon$. The newly developed wireless stress/strain measurement system integrated with pressure-sensitive nickel powder-filled cement-based sensors has such advantages as high sensitivity to stress/strain, high stress/strain resolution, simple circuit and low energy consumption.

## 5. Discussion and future works

### 5.1 Energy optimization

Due to the essence of the wireless sensing system, an external power connected by wires will not be used to supply the energy. Thus, it becomes an important issue to optimize the energy and reduce its consumption in wireless sensing technology. The problem of energy consumed is discussed from the point of node and network.

(1) For a node, the strategies of hardware, software, their cooperation are brought forward. For hardware of a wireless sensor node: Electronic components with low power consumption and high reliability are selected to integrate a wireless node, which reduces the overall power consummation and requires an energy source with high capacity. Regarding embedded software, it is known that a factor which plays an important role in the energy consumption is the volume of the transmitted data. The larger the volume is transmitted, the more energy is required. In this design, the data collected by the sensors are processed first, and only those describing the essential characteristics of the measured data are kept. This data are then packed and transmitted to the base station. In this way, the transmitted data volume is substantially reduced and energy is saved. To summary, saving power is accomplished by the cooperation between hardware and software.

(2) For the overall network, good algorithms with MAC and routing protocol are necessary for saving power. For example, in the time-sharing TDMA communication between the base station and the sensor nodes, only one sensor node is working at a time. The other sensor nodes are in idle, power-save, power-down or standby mode. In this way, the microprocessor and wireless transceiver in the working sensor becomes the main consumer of energy. The energy consumption of the overall network is reduced. In addition, an innovative method of Power Saving Ant Colony Optimization based on powers is presented and simulated in paper (Yu 2006), and the research shows that the above saving energy strategies can extend the work life of wireless sensor network.

### 5.2 Future works

The authors are trying to develop a kind of wireless array acceleration sensors with quick deployment and super low frequency sensing unit to monitor the vibration characteristic of offshore platform in deep sea so that the damage can be detected and repaired quickly. The authors are also designing a kind of wireless self-power corrosion monitoring system in concrete. All the components are embedded in monitored structure. Corrosion produces not only sensor signal but also charge power stored in a special capacitor, which means that wireless self-power corrosion monitoring system works while there is corrosion in concrete.

## 6. Conclusions

Some recent advances in research, development and implementation of wireless sensors networks for SHM of civil infrastructures are introduced. The following conclusions can be drawn:

(a) The wireless digital acceleration sensor may calibrate acceleration by itself according to the measured temperature to receive more accurate values, and the designed wireless sensor can measure the acceleration of a structure well.

(b) Wireless inclination sensors systems based on Frequency-Hopping can overcome the monitoring errors of unaided eyes without affecting the normal work of the monitored objective. Further experiment validates the effect of the proposed TMD control device.

(c) The proposed wireless acquisition systems of some sensing materials are used easily for the analysis of the characteristics of these materials for structural local monitoring.

(d) The problem of energy consummation is discussed from the point of node and network. In order to finish energy optimization, the wireless sensor can pre-process and pack the measured data to reduce the data volume to be transmitted. Its micro-processing unit can choose between the working mode and different sleeping modes. And the routing algorithm is very important for energy conservation.

In general, the wireless sensors designed for structural global and local monitoring of civil engineering structures are feasible. The design is preliminary and the improvement is necessary. More importantly, more tests and practical use need to be carried out.

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