Dynamic Deformation Monitoring Based on Wireless Sensor Networks

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Key words: deformation monitoring, wireless sensor networks, data acquisition, data processing

SUMMARY

As one of the most important technologies in the 21st century, the emergence of wireless sensor networks (WSN) has brought both opportunities and challenges for the development of deformation monitoring. Compared with traditional deformation monitoring techniques, deformation monitoring systems using a large number of low-cost sensor nodes, can get rid of cable shackles and achieve wireless, multi-hop and long-distance transmission of monitoring data, thus having advantages in automatic, continuous and real-time deformation monitoring. However, there still exist limitations of senor nodes in computing power, storage capacity and bandwidth. The present article reviews data acquisition and data processing techniques in deformation monitoring based on wireless sensor network. In terms of data acquisition, the paper focuses on the following issues: how to choose motes, sensors, and software systems to meet the needs of monitoring tasks; the influence of time jitters within and between nodes in data sampling and methods for time synchronization; the issue of data compression because of the large amount of data caused by high-frequency sampling; and the ways to deal with problems of data loss in the wireless transmission process due to environmental interference and other factors. For data processing, firstly the required data pre-processing techniques for acceleration monitoring data, such as static and dynamic tests, temperature calibration, and data de-noising are discussed. Then acceleration monitoring data analysis methods in time domain, frequency domain and modal domain are summarized. In time domain numerical integration is used to transfer acceleration to displacement. Power spectrum density function is calculated based on Fourier transform in frequency domain. As for modal domain, structural dynamics are utilized to identify the structure modal parameters such as natural frequencies, damping ratios and modal shapes.

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1. INTRODUCTION

In recent years many large constructions, such as bridges, towers and high-rise buildings, are emerging in China. Vibration and deformation will be caused by the influence of operating loads, winds, earthquakes and other external factors in these constructions. Too much deformation may affect their normal operations, or lead to localized damage or even collapse. In order to ensure the safety of these constructions in their operational phase, dynamic deformation monitoring must be taken to grasp their real-time health conditions. Although GPS has the advantages of high-precision, high-speed and all-climate working, it is susceptible to monitoring environment. The use of accelerometer, inclinometer, automatic tracking total station and other methods have limitations in high-precision dynamic monitoring, for they cannot meet the automatic, continuous and real-time dynamic monitoring requirements. Fortunately, the advent of wireless sensor networks[1] can make up for these shortcomings. Large numbers of wireless sensor nodes, getting rid of the shackles of cable, are set on the constructions to sample monitoring information dynamically, and the monitoring data can be transmitted wirelessly in multi-hop ways. Deformation monitoring with wireless sensor networks is time-and-effort-saving, convenient in setting up a network and low in cost.

Currently there are many studies on wireless sensor networks based deformation monitoring. Krishna Chintalapudi et al.[2][3] from University of Southern California combined Mica2 nodes with vibration cards to build a monitoring system called Wisden and tested the system in a seismic testing structure. Combined with 64 Micaz nodes with two different precision accelerometers, Kim Sukun et al.[4][5] from UC Berkeley deployed a 46 hops wireless sensor networks monitoring system for the Golden Gate Bridge to get the real-time health condition through continuous high frequency sampling. Researchers from University of Illinois[6][7] developed a wireless sensor networks monitoring system for Korean Jindo Bridge. They used Imote2 nodes with their own designed triaxial accelerometers and other sensors to continuously collect data to monitor the condition of the bridge. Researchers in Switzerland[8][9] formed a monitoring system for the Stork Bridge with Tmote-sky nodes and dual-axis accelerometers to obtain the vibration frequency of the bridge. Ou Jinping et al.[10][11] conducted multi-sensor structural monitoring studies and launched multi-sensor monitoring networks for Binzhou Yellow River Highway Bridge in Shandong and the Emperor Building in Shenzhen. Meanwhile Li Aiqun's research team[12] also built a multi-sensor wireless monitoring system for Runyang Bridge and conducted research in massive data management, analysis and safety assessment. W. S. Chan et al.[13] integrated GPS and accelerometer to conduct deformation monitoring studies on high-rise buildings. Hu Xiaoya et al.[14] conducted deformation monitoring tests on Zhengdian Bridge with home-made wireless nodes.

The studies of deformation monitoring based on wireless sensor networks can be divided into two parts: data acquisition and data processing. Reliable and efficient monitoring data acquisition is the prerequisite for data analysis. Through data analysis we can grasp the health condition of the structures in their operational phase and make assessments. However, wireless sensor nodes have limitations in storage capacity, calculation ability, bandwidth and energy supplement, so there are still some problems to be solved in order to achieve large-scale applications. This paper reviews key issues in deformation monitoring based on wireless sensor networks data acquisition, such as hardware and software selection, clock synchronization, data compression and data loss, and discusses the vibration monitoring data processing methods in time, frequency and modal domain. The aim is to promote the development deformation monitoring based on wireless sensor networks in theoretical researches and engineering applications.

2. DATA ACQUISITION

The deformation monitoring framework based on wireless sensor networks is shown in Figure 1. Data acquisition is an important issue because reliable and efficient monitoring data acquisition is the prerequisite for data analysis. However, the resources of wireless nodes are limited. There are still some key issues ranging from hardware and software selection to data sampling and transmission to be solved in order to achieve the goal.

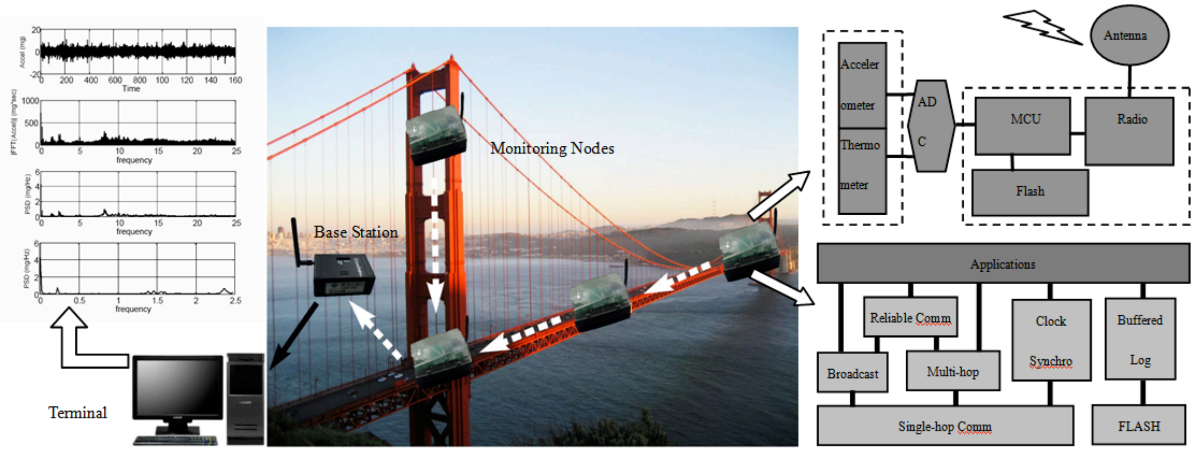

Fig. 1 Deformation Monitoring Framework Based on Wireless Sensor Networks Monitoring

2.1 Hardware and Software Selection

Wireless sensor nodes used to monitor structures consist of sensors, whose functions are to obtain the environmental information and the wireless motes, with which the information can be processed and transmitted. Usually the information needed is the vibration of structures, so the most commonly used sensors are accelerometers, together with strain gauge, anemometer and other sensors as complement. The selection of accelerometers should take range, sensitivity, noise, sampling rate, analog-to-digital conversion resolution and cost into account[15]. And whether to select uniaxial accelerometers to monitor one direction's vibration or multi-axis accelerometers to get vibration information in many directions depends on the requirements of the monitoring tasks.

The main parts of the wireless motes comprise processing units and communication units. As the processing units, the microcontroller chips integrate all the necessary components like arithmetic unit, controller, memory, bus, input and output. Microcontrollers are characterized by limited computing power, low power cost and high reliability, making them popular in wireless sensor networks applications. Currently the commonly used microcontrollers in motes are MSP430 series, AVR series and ARM series. The basic function of the communication units is to transmit sampled monitoring data wirelessly to the base station. When the data can not reach the base station directly, the relay motes will be needed. The communication units are also responsible for receiving control commands from the base station. The selection of communication units is a trade-off between the communication range and energy consumption. Commonly used radios in wireless motes are CC1000, CC2420 and AT86RF230 etc. Wireless sensor nodes are generally battery-powered, making energy saving an important issue in wireless sensor networks applications. There are studies on using environmental vibration or solar energy to provide continuous energy at present[16]. Several typical motes used in deformation monitoring based on wireless sensor networks include Mica series, Imote2, Tmote-sky and so on. Table 1 shows the composition of the motes and the sensors they carry in these monitoring cases.

Tab. 1 Motes and Sensors in Typical Monitoring Cases

Monitoring Case	Mote	Institute	MCU	Radio	Sensors
Seismic Test Structure	Mica2	Computer Science Department, University of Southern California	Atmega128L	CC1000	Vibration card
Golden Gate Bridge	Micaz	Civil and Environmental Engineering, UC Berkeley	Atmega128L	CC2420	Dual-axis accelerometer, thermometer
Stork Bridge	Tmote-sky	Structural Engineering Laboratory, Empa Dübendorf, Switzerland	MSP430	CC2420	Dual-axis accelerometer, thermometer
Jindo Bridges	Imote2	Department of Civil and Environmental Engineering, University of Illinois at Urbana-Champaign	Intel PXA271	CC2420	Triaxial accelerometer, thermometer, hygrometer etc.
Zhengdian Bridge	S-Mote	Department of Control Science and Engineering, Huazhong University of Science and Technology	MSP430F1611	CC2420	Dual-axis accelerometer, strain gauge

Software in wireless sensor networks is responsible for managing sensors, radio, power and other resources. In order to lower difficulties in development, cut down time and cost, embedded operating systems are needed to abstract the underlying hardware. Considering wireless sensor networks' adaptability, robustness, fault tolerance and operating system's portability across different hardware platforms, existing embedded operating systems can not meet the requirements of wireless sensor networks applications. New operating systems need to be developed based on the features of wireless sensor networks and several institutes have developed operating systems for wireless sensor networks, like TinyOS, Mantis OS, SOS and Contiki operating systems. TinyOS[17], developed specifically for wireless sensor networks by UC Berkeley, is an open source embedded operating system. It has component-based architecture, event-driven model and active message mode, making it easy for users to achieve their purposes. The system itself and its application programs are programmed by nesC[18] language through composing and connecting components and providing and using interfaces. TinyOS is the dominant operating system for wireless sensor networks. It supports different types of wireless nodes and all the softwares in the typical monitoring cases above are implemented by TinyOS. Mantis OS[19] and SOS[20] are wireless sensor networks operating systems developed by University of Colorado and UC Los Angeles respectively. Both systems are implemented by standard C language and their designs take the features of wireless sensor networks into account. Although not supporting as many platforms as TinyOS, the two systems still have several successful applications. Contiki[21], a multiple task operating system designed for embedded system by Swedish Institute of Computer Science, supports network connection and has small code size and high portability, which suits resource-limited wireless sensor nodes. It has been transplanted to a variety of platforms and can provide alternatives for the development of wireless sensor networks software.

2.2 Data Sampling

For environmental monitoring tasks, such as temperature and humidity, the sampling rate is very low and the data size is small, so most of the time wireless sensor nodes stay in sleep mode. While for deformation monitoring tasks based on wireless sensor networks, continuous high-frequency sampling is needed in order to grasp the real-time deformation information of constructions. According to the Nyquist sampling theorem, the sampling rate must reach twice the signal bandwidth to accurately reconstruct the original signal. The natural frequency of most structures is between several Hz and a hundred Hz. If the natural frequency is set as F, the sampling rate of the accelerometer needs to be at least $2F$ in order to recover the vibration information of the structure. And the sampling rate needs to be further improved due to the high damping characteristics of structures and the requirement of improving signal to noise ratio. Take the Gaussian white noise σ for example, when the sampling rate improves to $2NF$, the impact of noise will reduce to $\sqrt{N}\sigma$, then the sampling rate can reach as high as KHz[22], resulting in a huge data volume and the issue of time jitter.

The data size of a sampling unit is set as 16bit. When the sampling rate is 1000Hz, a node can produce 165M data during the 24 hours' continuous monitoring. Such a huge amount of data is unfavorable to resource-limited sensor nodes for bringing challenges for bandwidth-limited wireless networks to send data to the base station. Therefore, how to reduce the size of sampling data without distortion becomes critical. The emergence of compressive sensing brings hope for the issue of cutting down the size of data. If the original signal is sparse and compressible, the wireless senor nodes can make non-adaptive linear projection of signals with a much lower sampling rate than that of the Nyquist theorem, and then the signal can be recovered by using appropriate reconstruction algorithms[23]. The idea is to directly sample the compressed signal, simplify the sampling workload and leave the complex reconstruction work to the terminal, which suits resource-limited wireless sensor networks applications very well. But currently this technology is still under theoretical researches and there is a long way to go before practical applications.

The time jitter in data sampling is shown in Figure 2. It can be divided into temporal time jitter and spatial time jitter. The temporal time jitter occurs when the senor node can not maintain the equal sampling interval under high-frequency sampling condition and non-equal sampling can affect data processing. Temporal time jitter is caused by wireless sensor node software system in which the preempted tasks will affect the sampling task, that is, sampling tasks can be blocked and delayed by non-preemption tasks. Proper software programs should be designed to ensure the priority of sampling tasks and that the error stays within the allowable range. The spatial time jitter is also known as the issue of time synchronization. Since each node only maintains its own local clock, when they don't start or receive acquisition commands at the same time, clock errors among different sensor nodes will arise, and meanwhile clock frequency offset and drift may make the clock errors become larger and larger. The disorder concerning time of sampled data makes data processing and data analysis difficult. So the sensor nodes in the monitoring network must be periodically synchronized to be controlled in the same reference of time. So far a variety of time synchronization mechanisms for wireless sensor networks have been proposed, such as reference broadcast synchronization protocol RBS[24], wireless sensor network time synchronization protocol TPSN[25] and flooding time synchronization protocol FTSP[26] etc. In wireless sensor networks dynamic monitoring applications, Ning Xu et al.[15] used a timestamp-based data synchronization technology to synchronize all the collected data at the base station. More researchers used the existing FTSP[27] protocol in their applications. Due to the different considerations of different implementations of time synchronization protocols, such as complexity, synchronization accuracy, energy efficiency and other factors, existing time synchronization protocols may not be entirely suitable for the requirements of wireless sensor networks monitoring applications. Combined with the existing synchronization protocols, data sampling rate, the required time synchronization accuracy and the stability of the clock should also be taken into account to design time synchronization mechanism which suits wireless sensor networks dynamic monitoring tasks.

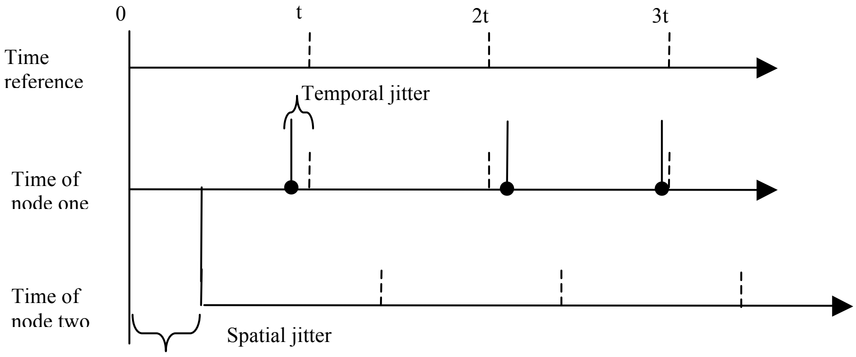

Fig. 2 Time Jitter in Data Sampling

2.3 Data Transmission

The raw monitoring data sampled at wireless sensor nodes needs to be transmitted to the terminal for analysis. Because of the big size of data and limited bandwidth, data compression and data loss became major issues in data transmission.

The purpose of data compression is to reduce storage space and improve the transmitting, storing and processing efficiency. According to the reversibility of the compression mechanism, data compression algorithms can be divided into lossless and lossy data compression. Data compression is widely used in image processing. For example, JPEG2000[28] standard uses wavelet transform to compress the original image to remove redundant data. In wireless sensor networks dynamic monitoring applications, high frequency sampling is required in order to capture the vibration information of structures, leading to a huge data size, which is unfavorable for bandwidth-limited wireless sensor nodes. Then raw monitoring data must be compressed before transmission. Krishna Chintalapudi et al.[29] used run-length encoding compression technique in wireless sensor networks monitoring tests. Lynch et al.[30] utilized Huffman coding to compress the raw monitoring data. And Flouri e et al.[9] transferred the data into frequency domain before transmission. S. Pakzad et al.[31] adopted pipe transmission technology to reduce the transmission delay. Bao Yuequan et al.[32] analyzed the performance of compressive sensing in acceleration data compression. The assessment of data compression methods in dynamic monitoring based on wireless sensor networks should take compression ratio, recovery error, energy consumption, propagation delay and complexity into consideration. According to the studies of Quer et al.[33], monitoring data collected by sensor nodes have correlations. Then distributed data compression algorithms, such as distributed KL transform, distributed wavelet transform and distributed compressive sensing[34], became meaningful in improving the performance of data compression in wireless sensor networks monitoring as they take the temporal correlation within the sensor node and spatial correlation between the sensor nodes into account.

Monitoring data collected by sensor nodes must be transmitted to the terminal accurately. Incomplete data will bring difficulty for data processing. But wireless sensor nodes have limited communication range; multi-hop relaying may be needed when senor nodes are far from the base station. Wireless transmission is more vulnerable to interference in the environment than wired transmission, thus causing data loss. Therefore, the reliability of monitoring data is also an important issue in data transmission. Current studies are done from two aspects: design of reliable transport protocol and recovery of lost data.

The design of reliable transport protocol design includes data collection and command distribution. The protocol should ensure that monitoring data goes to the terminal without error and it should also make sure that commands can be sent to each sensor node correctly so that each node can complete the required data sampling tasks. Data transport protocol includes loss detection and retransmission. Commonly used data collection protocols in wireless sensor networks include RMST, RBC, ESRT, PORT, and STCP and commonly used command distribution protocols include PSFQ and GARUDA. For wireless sensor networks monitoring applications, Ning Xu et al.[15] used hop-to-hop and end-to-end method to retransmit lost data. Kim Sukun et al.[4] designed Straw transport protocol to ensure the reliability of monitoring data in multi-hop transmission. Nagayama et al.[35] also designed a reliable communication protocol for dynamic monitoring based on wireless sensor networks. The energy consumption, cache size, complexity and robustness should be considered when designing reliable data transport protocol for wireless sensor networks. Another solution for data loss in transmission is to recover it at the terminal. Allowing data loss during the transmission by analyzing the tolerance rate, the lost data can be recovered at the terminal through appropriate algorithms. Commonly used recovery technique is data interpolation[36]. Bao Yuequan et al.[37] conducted studies on data recovery technique based on compressive sensing. Data recovery strategy reduces data retransmission rate, thus saving network resources.

3. DATA PROCESSING

The monitoring data needs to be processed timely after the terminal receives it from the wireless sensor networks in order to grasp the health condition of structures. For acceleration monitoring data, the main data processing methods include time domain, frequency domain, and the modal domain analyses. Meanwhile some preprocessing is required before the data analysis.

3.1 Data Preprocessing

Preprocessing of acceleration monitoring data includes static and dynamic testing, temperature correction and data de-noising. The purposes of static and dynamic testing are to calibrate the acceleration sensors. Usually a highly precise accelerometer is used to sample data in static and dynamic environment together with the being calibrated acceleration sensors. Through comparison the offset in static environment and the dynamic response can be detected and only the calibrated acceleration sensors can be used in dynamic monitoring of structures.

Since most sensitive components of the acceleration sensors are made of metal or semi-conductive materials, sampling data can be easily affected by temperature which generally changes a lot in monitoring environment, resulting in deviation of the output values of the acceleration sensors. Therefore, temperature sensors are needed to record real time temperature information in monitoring environment to correct the output values of the acceleration sensors. By recording the output values of the acceleration sensors, the actual values and the temperature information, the corresponding correction model can be built. Then the acceleration output values can be automatically corrected in data sampling procedure through the temperature correction module. Commonly used temperature correction model is linear regression model[38].

The monitoring data will inevitably introduce noise in the process of data acquisition and wireless transmission due to various factors. In order to reduce or eliminate the impact of noise in data analysis, de-noising preprocessing must be conducted on monitoring data. De-noising techniques used for vibration data include median filtering, Kalman filtering and Vondrak filtering etc. Wavelet analysis and empirical mode decomposition are also widely used in data de-noising. After de-noising process, the acceleration monitoring data can be used for analysis.

3.2 Data Analysis

For large structures, monitoring vibration data analysis is modal parameter identification based on structural dynamics. By identifying the natural frequency of the structure, damping ratios, mode shapes and other parameters, it provides a basis for structure assessment. According to the features of data collected through wireless sensor networks, the modal parameter identification method based on ambient excitation is often used, and data analysis is conducted in time, frequency and modal domains.

In time domain, sometimes the vibration signals collected by sensor nodes need to be converted into velocity and displacement signals, which is often obtained by integration process. The vibration signal collected by a sensor node in one direction is set as $a(t)$, then the velocity signal is as follows:

$$v(t) = \int_0^t a(t)dt = v'(t) + v_0 \tag{1}$$

The displacement signal:

$$s(t) = \int_0^t v(t)dt = s'(t) + s_0 \tag{2}$$

Another basic method of processing random vibration signals collected by sensor nodes in time domain is to calculate the correlation function. Correlation function describes the degree of correlation between instantaneous values of random vibration signals at different moments, including autocorrelation function and cross-correlation function. Autocorrelation function describes the correlation between vibration signals collected by a certain sensor node over time, and its discrete expression is:

$$R_{xx}(k) = \frac{1}{N}\sum_{i=1}^{N-k} x(i)x(i+k)(k = 0,1,\ldots,m) \tag{3}$$

$x(i)$ represents the discrete vibration signal of a sensor node.

Cross-correlation function describes the correlation between vibration signals collected by different sensor nodes over time, and its discrete expression is:

$$R_{xy}(k) = \frac{1}{N-k}\sum_{i=1}^{N-k} x(i)y(i+k)(k = 0,1,\ldots,m) \tag{4}$$

$x(i), y(i)$ represent the vibration signals collected by two different sensor nodes.

In frequency domain, the main processing method is to calculate the power spectral density function of the random vibration signal based on Fourier transform. It represents the statistical average spectral properties of the signal, and can be divided into self-power spectral density function and cross-power spectral density function. The power spectral density function of vibration signals collected by a single sensor node is called self-power spectral density function, which is the Fourier transform of the autocorrelation function. Its discrete expression is:

$$S_{xx}(k) = \frac{1}{N}\sum_{r=0}^{N-1} R_{xx}(r)e^{-j2\pi kr/N} \tag{5}$$

$R_{xx}(r)$ represents the autocorrelation function of a sensor node.

The power spectral density function of vibration signals collected by two different sensor nodes is called cross-power spectral density function, which is the Fourier transform of the cross-correlation function. Its discrete expression is:

$$S_{xy}(k) = \frac{1}{N}\sum_{r=0}^{N-1} R_{xy}(r)e^{-j2\pi kr/N} \tag{6}$$

$R_{xy}(r)$ represents the cross-correlation function of two different sensor nodes.

The methods to calculate power spectral density function can be divided into non-parametric approach and parametric one. Non-parametric approach calculates the power spectral density function based on its definition. Commonly used methods include periodic table, correlation diagram and method based on improvements of the two. Parametric method assumes that the signal fit the model parameter of the known function, and estimates the model parameters.

Analysis in modal domain is to identify the modal parameters. Only structural response is used to identify the modal parameters in modal parameters identification under ambient excitation and the ambient excitation is unknown, which is usually assumed to be white noise. Modal parameters identifications can be divided into methods in time and frequency domains according to data processing mode.

Time domain method directly uses vibration data collected by sensor nodes to identify the modal parameters. Commonly used methods are time series, random decrement, NExT, stochastic subspace and modal function decomposition. Time series method uses stochastic process and theories of mathematical statistics to model data for identifying the model parameters. It includes autoregressive model (AR), autoregressive model exogenous (ARX), moving average model (MA) and autoregressive moving average model (ARMA). Random decrement technique removes the random component of the response data using the expectation of the sampling function to get the free vibration response of acceleration data, and then uses the traditional methods for parameter identification. The basic idea of NExT is that the cross-correlation function of two points in structure has similar expression with the impulse response function. By selecting a reference point to calculate the correlation function of sampling data, traditional methods can be used for modal parameter identification. Stochastic subspace method is suitable for stationary excitation. It is based on the discrete linear system state-space equation, which identifies modal parameters by calculating the state-space matrix and output matrix of the state-space equation. Modal function decomposition first calculates the response of white noise ambient excitation based on NExT, then conducts modal function decomposition to get the step modal functions and last obtains modal parameters through Hilbert transform.

Modal parameter identification in frequency domain includes the peak picking method and frequency domain decomposition method. Due to the difficultly of getting the frequency response function of the structure, the peak picking method uses the power spectrum function for modal parameter identification instead of frequency response function, which is based on the fact that the peak of frequency response function appears near the natural frequency. This identification method has large error, but is easy and fast. Frequency domain decomposition method improves and extends the peak picking method. It decomposes the power spectrum of response to a set of single degree of freedom power spectrums through singular value decomposition. Frequency domain decomposition method overcomes the disadvantage of the peak picking method and has high identification accuracy.

4. CONCLUSION

The advent of wireless sensor networks is based on the development of micro-electromechanical systems (MEMS), system on chip (SoC), wireless communications and embedded technologies. It brings new ideas for structures' deformation monitoring with the characteristics of low power consumption, low cost, being distributed and self-organized. However, due to the limited resources, there are still several key issues to be resolved in practical applications. In terms of data acquisition, proper selection of hardware and software can meet the demand of monitoring projects and reduce costs at the same time and existing case studies provide references for practical applications. The issue of huge data size brought by high-frequency sampling needs to be solved with new theories, which can overcome the limit of Nyquist theorem. The temporal and spatial time jitter can affect the validity of sampling data, which should be addressed with appropriate mechanisms combining with existing time synchronization algorithms and requirements of deformation monitoring. For data transmission, the purpose is to reduce storage space and improve transmission efficiency. For big size of monitoring data, distributed compression algorithms should be used according to the features of wireless sensor networks. The reliability of monitoring data can guarantee the data analysis and the two research directions are design of reliable transport protocol and recovery of lost data . In data processing, preprocessing can promise the usability of vibration data. Modal parameters identification under ambient excitation using structural dynamics theories provides the basis for health assessments for structures. In short, with data sampling, data transmission and data processing problems gradually resolved, wireless sensor networks based deformation monitoring will play a significant role in civil engineering.

ACKNOWLEDGMENT

This work was funded by Key Laboratory of Advanced Engineering Surveying of National Administration of Surveying, Mapping and Geoinformation (TJES1202).

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