16th Australasian Wind Engineering Society Workshop
Brisbane, Australia
18-19 July, 2013

Wireless Typhoon-Induced Vibration Measurement System for Super High-Rise Building Structures

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Abstract

This paper presents a Typhoon-induced Vibration Measurement System based on wireless sensor networks for the application of super-high building Structures vibration inspection.

The designed system consists of intelligent acquisition equipment and 8 wireless nodes with low-frequency acceleration sensor. The whole system has 64 collection channels, namely every wireless collection node has eight 16-bit A/D channels.

Wireless node, integrated with vibration sensing unit, embedded low-power micro-processing unit, wireless transceiver unit, large-capacity power unit, and GPS time synchronization unit, can finish the functions such as data collection, initial analysis, data storage, data wireless transmission.

Intelligence acquisition equipment, integrated with high-performance computation unit, wireless transceiver unit, mobile power source and embedded data analysis software, can totally control multi-wireless nodes, receive and analyse data, parameter identification.

To verify the SYSTEM, experiments on the standard horizontal vibration table (shake table Ⅲ) and super-high building of Diwang Plaza are conducted. Experimental results show that the system has the following characteristics as fast arrangement, high sampling rate, high resolution, capacity of low frequency inspection, and thus has good application prospects and practical value.

Introduction

Recently, more and more super-high buildings appear(shown in table 1), and these super-high building suffer damages caused by environmental loads, fatigue, caustic effect and material aging, such side effects as damage accumulation, resistance reduction and even accidents happen inevitably during the service time.

In order to keep large engineering structures in good order, structural health monitoring (SHM) should be performed. The first important component in a SHM system is a set of appropriate sensors. For structural health monitoring, wired sensing network is a kind of main collection mode. But having low-reliability, the wired sensing network needs plenty of wire and costly maintenance fee, and even is applied impossibly to some special structures. Fortunately, with the development of sensing, wireless communication and MEMS (micro electro mechanical systems) technologies, it has been an important research hotspot to apply wireless and sensing technologies to engineering structure monitoring step and step.

Generally, the sensor information is transmitted by wire. But wire acquisition system for super-high buildings is huge consumption of wires and very difficult for cabling work. And because there are lots of wires, it is hard to find out the broken wire, which leads to high maintenance costs. At the same time it will consume large amount of manpower and capital during the cabling work.

	Building, City	**year**	**floors**	**Height** (m)
1.	Taipei 101, Taipei,	2003	101	508
2.	Petronas Tower 1, Kuala Lumpur, Malaysia	1998	88	452
3.	Petronas Tower 2, Kuala Lumpur, Malaysia	1998	88	452
4.	Sears Tower, Chicago	1974	110	442
5.	Jin Mao Building, Shanghai	1999	88	421
6.	International Finance Center, Hong Kong	2003	88	412
7.	Citic Plaza, Guangzhou,	1996	80	391
8.	Shenzhen(Diwang Plaza)	1996	79	384
9.	Empire State Building, New York	1931	102	381
10.	Central Plaza, Hong Kong	1992	78	374
11.	Bank of China Tower, Hong Kong	1989	70	369

Table 1. Typical super-high buildings

Based on this, a Wireless Typhoon-induced Vibration Measurement System is designed and validated in this paper.

System Architecture

The system architecture is shown in Figure 1. The designed system consists of one intelligence acquisition equipment and 8 wireless collection nodes, the whole system has 64 collection channels, and namely every wireless collection node has eight 16-bit A/D channels. Data is transmitted at 2.4GHz wireless channel, every sensing data channel in charge of data transmission is in a stable frequency band.

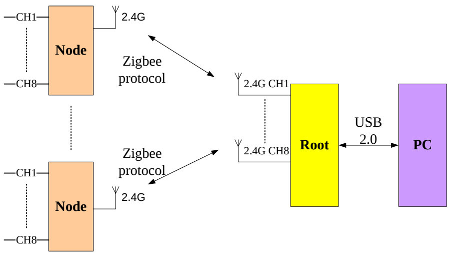


Figure 1. This is the system structure.

Design of Low-Frequency Wireless Acceleration Sensor

Studies show that it is possible to get safety assessment of the super-high buildings based on the modal information by making global dynamic inspection to the platform regularly.

And structural global inspection technology of super-high buildings can overcome the limitations of local inspection. The global inspection technology can verify design assumptions, monitor construction quality and make real-time safety status assessment; especially it can work without external auxiliary excitation based on dynamic inspection. So the global inspection technology which is indispensable technical means has great advantages.

The structure of low-frequency wireless acceleration sensor is shown in Figure 2. The wireless acceleration sensor node which is modular designed consists of low-frequency acceleration sensor, sensor interface unit, micro processing unit, wireless transceiver unit, storage unit and power management unit 5-6.

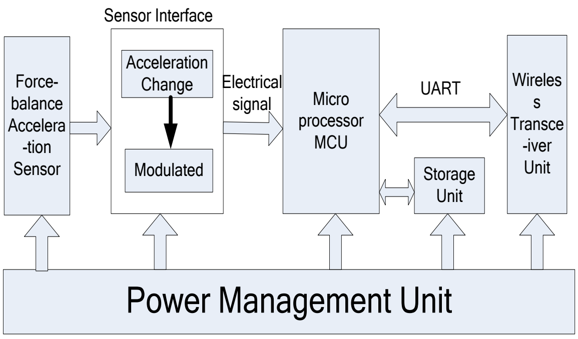


Figure 2. Structure of ultra-low-frequency wireless acceleration sensor

Selection and Analysis of Sensor Unit

In the designed system, force-balance sensor is used for the low frequency vibration measurement unit.

Force-balance acceleration sensor is closed-loop one which converts data to force or moment of force firstly, then adjusts the balance system with feedback force.

Force-balance acceleration sensor with huge dynamic range and high measurement precision is used in low frequency and low-g measurement, and is the crucial unit in inertial navigation system. With the good performance in ultra-low frequency, force-balance acceleration sensor can meet the needs of low frequency vibration inspection.

Sensor Interface

Wireless nodes support force-balance acceleration sensor which needs ±12V power supply, and outputs ±2.5V or ±5V analog voltage signal.

Wireless nodes use multi-way switch chip MAX4051 to process 8 channels selection firstly, and then use 24bit high accurate ADC chip ADS1248 to convert analog signal to digital signal. ADC system has to generate ±2.5V and ±5V power supply using LM4040A to generate all kinds of power supplies.

Micro Processor and Storage Unit

Micro processor use TI high performance 16bit micro processor MSP430F5438. The series micro processor has the lowest operating power consumption; the performance is up to 25MIPS at 1.8V-3.6V operating voltage range, and can meet the design needs of wireless sensor in low power consumption and high rapid data processing.

Storage unit uses NAND large capacity flash memory.

Wireless Transceiver Unit

Wireless transceiver unit is for data wireless transmission, consists of such Zigbee wireless chip as CC2520 RF chip and enlarge front CC2591. CC2520 RF chip is 2.4GHz license-free ISM band Zigbee/IEEE 802.15.4 second generation RF transceiver of TI Company.

CC2591 is 2.4GHz RF front end unit for low power consumption and low voltage wireless application, can improve the transmission power and receiving sensitivity, and increase the wireless signal strength and transmission distance.

Power Management Unit

In the designed system, 24v battery is selected as wireless node's power source for rapid measurement and continued power supply. Because each unit in the system needs different power supply, such as ±15V、±12V、+3.3V, and analog circuits require a higher voltage ripple, so energy design has two-stage transformation structure.

The first stage uses DC/DC chips for the transformation from +24 V to ± 15V and +3.3 V. The second stage uses LDO chips 7812 and 7912 for the transformation from ±15V to ±12V.

The wireless node, shown in Figure 3, is integrated using the above units.

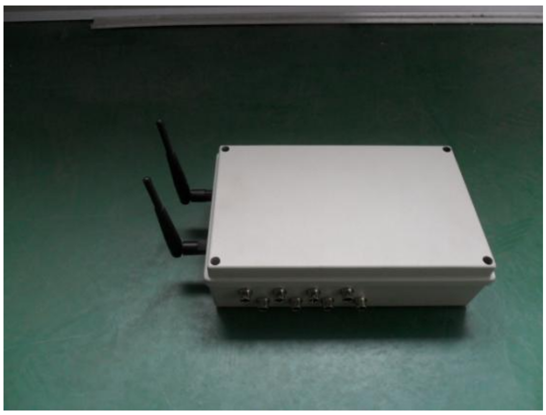


Figure 3. Wireless sensor node

Software Design of Wireless Low Frequency Vibration Acquisition System

The software of wireless low-frequency vibration acquisition system for super-high buildings inspection consists of two parts: embedded program of wireless node and the host PC acquisition software.

Embedded Program of Wireless Node

The embedded program, integrated with ADC driver, storage driver, wireless driver, preliminary data analysis and diagnosis and so on, can control circuits, receive command from the host for parameters setting, data acquisition, processing, storage and transmission.

Every wireless node's workflow is as follows: the wireless node, powered up in the wireless receiving state, does not work until receiving the command from host. Among acquisition, host firstly finishes the parameters setting to all wireless nodes, then sends start or stop command to control data acquisition. The wireless node can collect the vibration data of the super-high buildings for inspection.

Host Acquisition Software

The host acquisition software mainly completes the parameter setting of the wireless node, data collection, data export, data storage, data analysis and process.

Using a modular design consists of the basic setting, real-time waveform monitoring, history waveform playback, data export, help document and other modules. The acquisition software's modules are shown in Figure 4.

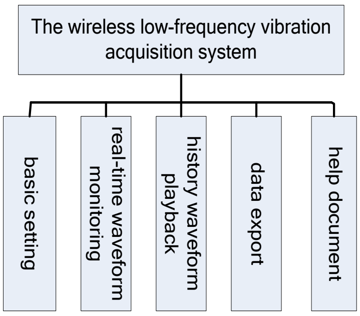


Figure 4. Host acquisition software's modules

Basic setting is used to set the state of wireless sensors, wireless transmission channels, sampling frequency, file storage path and other parameters on demands.

Real-time waveform monitoring can display the collected data's real-time waveform, and write the data in database.

History waveform playback could show a playback of history waveform based on the data collected, to facilitate analysis.

Data export could export the data collected from a specific wireless node at certain channel and time to a certain file for further analysis and process.

Help document give some help information for the users who use this acquisition software.

Experiments and Analysis

Experiment on the Standard Horizontal Vibration Table using SYSTEM

To verify the designed wireless low-frequency acceleration sensor, experiment on the standard horizontal vibration table (shake table Ⅲ) is constructed.

The wireless node is arranged in the horizontal vibration table's center at X- direction, communicating with the host's wireless receiver unit, and capturing the horizontal acceleration signal. Composition and field test of experiment are shown in Figure 5.

Vibration control device produces the amplitude 0.03m, frequency 0.1Hz and 0.5Hz horizontal vibration to simulate the typhoon-induced vibration waves of super-high buildings. The host sets the sampling frequency as 100 Hz.

The collected acceleration data is processed, analyzed in time and frequency properties. Time and frequency analysis of 0.1Hz and 0.5Hz are shown in Figure 6.

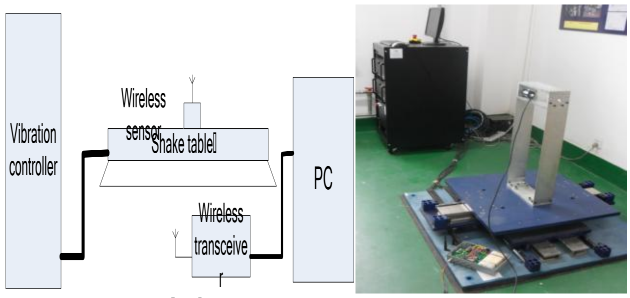
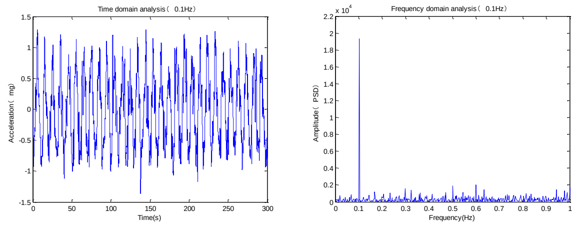
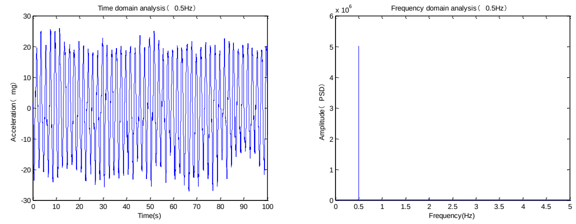


Figure 5. Horizontal vibration experiment



(a)Time and frequency analysis of 0.1Hz



(b)Time and frequency analysis of 0.5Hz

Figure 6. Data analysis

Through the time and frequency analysis of 0.1 Hz and 0.5Hz vibration signal, it is shown that the wireless sensor node has high reliability and good low-frequency performance, especially in frequency domain, as shown in table 2.

The experimental result shows that the wireless low-frequency acceleration sensor and its acquisition software can collect acceleration data to reflect the real low-frequency horizontal vibration.

It is suitable for the super-high building's low frequency vibration detection.

Reference frequency	Measured frequency	Relative error
0.1Hz	0.102	2%
0.5Hz	0.504	0.8%

Table 2. Error analysis of frequency

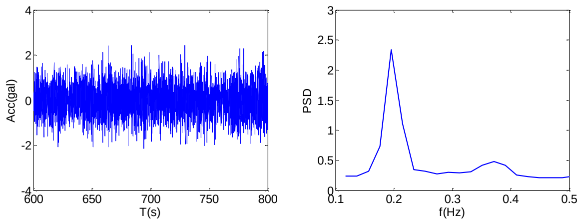
Typhoon-induced Vibration Monitoring in Diwang Plaza

Located in the central district of Shenzhen City, China, Diwang Plaza was built in 1996. As a typical super high-building, it is 325 meters tall, and 384 meters added with two backstays. Consisting in 79 floors, Diwang Plaza belongs to super-high building. The experimental objective is to test the structural vibration using wireless sensors while in typhoon. Four wireless sensors are put on the M floor to measure the two orthogonal accelerations of the building, and wired acceleration sensors are put on the corresponding place to validate the wireless sensors.

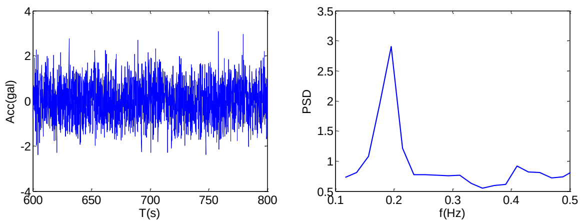
The super-high building is shown in Figure 7.

Figure 7. A picture of Diwang plaza

The vibration data of Diwang Plaza is gathered wirelessly while in the typhoon. The testing wave shapes are shown in Figure 8 and Table 3 shows the central frequency comparison among wireless sensor, wired sensor and finite element model.



(a) Wired



(b) Wireless

Figure 8. Testing wave shape of wired and wireless sensors

	wireless	**wired**	**Finite element model**
1st(Hz)	0.195	0.185	0.168

Table 3. The central frequency comparisons

Based on the wave forms, it can be discovered that when typhoon occurs, amplitudes of structural vibration acceleration become noticeable larger compared to structural vibration response under non-typhoon period. The wireless acceleration sensor can effectively captures the structural vibration response during the typhoon event. The comparison of the cental frequency shows that the error between wireless sensor (frequency 0.195Hz) and the wired sensor (frequency 0.185Hz) is within 5%. Therefore, the wireless sensor can reflect the central frequency of the structure with acceptable accuracy. While both measured results are significantly greater than the finite element analysis results (0.168Hz) due to non-structural elements have not been adequately considered in the numerical model, but play a significant impact on structural dynamics. Nevertheless, the wireless sensor is shown to be able to capture the acceleration response of the super-high building structure and can reflect the changes between the structural acceleration response and wind loading.

Conclusions

The following conclusions can be achieved: (a) the wireless measurement system can capture typhoon-induced vibration of high-building structure, (b) the sensor nodes are fixed and removed expediently and thus save installing time and the capital cost, which is fit for fast measuring the vibration of high-building structure in emergency, (c) the wireless measurement system has the following characteristics as high sampling rate, high resolution, capacity of low frequency inspection, and thus has good application prospects and practical value.

Acknowledgments

Financial supports for this study provided by grant from National Natural Science Foundation of China (Project No. 51108060, 51161120359， 50921001), the natural science foundation of Liaoning Province (201202039), National Key Technology Research and Development Program during the Twelfth Five-Year Plan Period (Project No.2011BAK02B01), the Fundamental Research Funds for the Central Universities (Project No. DUT12JR13), are gratefully acknowledged.

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