A Wireless Multifunctional Monitoring System of Tower Body Running State Based on MEMS Acceleration Sensor

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Abstract

This paper proposes a design of wireless monitoring system of tower body running state such as tilt angle, temperature, humidity, wind speed, etc. This design adopts the structural health monitoring (SHM) techniques to monitor the state of tower, and can be applied to both the power transmission tower and the communication tower. Although the SHM has been widely applied to civil engineering and building structures subjected to various loadings, there are few applications in the running state monitoring for the power transmission and communication towers. In this study, micro-electro-mechanical system (MEMS)-based acceleration sensor is used, in which a method is employed for calculating the tilt based on the difference between the acceleration due to combination of gravity and other stresses and the acceleration due to gravity alone. The wireless system uses wireless sensor nodes to transmit the tower running state data to the monitoring server. The wireless sensor node system consists of a short-distance wireless transmission network (ZigBee 2.4GHz) and a remote telecommunication network (Global System for Mobile Communication - GSM). By so doing, the important problem about the communication distance limitation is resolved. The performance of the monitoring system is evaluated through several experiments. The experimental results indicate the wireless monitoring system can accurately monitor the tower body running state in real time.

Keywords

Wireless monitoring; structural health monitoring; angle of tower body; MEMS-based acceleration sensor; remote transmission

1. Introduction

With the rapid development of power industry, there is always mismatching between the power generation and the power consumption due to the unbalanced distribution of the resources. Long-distance power transmission still uses overhead transmission lines in most places, and thus the transmission tower is an important part of the transmission line as the support for overhead line.

The tower is usually placed in the wild and even remote mountainous area, and thus the tower body could be tilted or even collapse due to a harsh external environment such as ice cover, geology settlement and other environmental factors. Two examples are shown in Figure 1. It was found that these accidents can be initiated from tilt. The tilted or collapsed tower can affect the work of power transmission and mobile communication and is difficult to keep good maintenance in remote mountainous area, which could lead to a huge economic loss. For instance, the snow disaster in southern China in early 2008 brought great loss to the power grid. Therefore, the study about the status of tower with a real-time monitoring is important for practical application.

(a) (b)

Figure 1: Tilted and collapsed tower

The major measurement parameters used in evaluating the status of the tower body are tilt angle (with respect to the vertical direction), amplitude, oscillation frequency, temperature and humidity. These dynamic characteristics of the tower body can be measured and calculated by using acceleration sensors. Acceleration sensors for tilt measurements have been widely applied in many industrial applications and many successful applications have been reported [1][2][3]. The SHM technology, automotive, electronics, and aviation industries are among the major areas of applications [4][5][6]. The MEMS-based inclinometer has been used to monitor the civil engineering and building structures (using the SHM technology) and the principle is based on measuring the changes in the tilt caused by the acceleration due to gravity [7].

The sensing module to the tower body usually requires low power, low weight, small size, and good accuracy. The micro-electro-mechanical system (MEMS)-based acceleration sensors meet these requisitions. With the development of MEMS technology, MEMS-based acceleration sensors are highly applicable to SHM for monitoring. Moreover, there is another important merit about the wireless transmission. That is, wireless communication has the ability to overcome the difficulties due to the harsh external environment.

With rapid development of sensor technology, MEMS and wireless communications, the wireless sensor network (WSN) has wide applications. For example, a monitoring system has been designed for monitoring forest fires based on the wireless sensor network and GPRS network [8]; a few structural systems have been monitored using the wireless smart sensor networks (WSSN) measuring acceleration, temperature, wind speed, humidity [9]; the wireless sensor network (WSN) has been widely proposed as a solution to improve the reliability, productivity and safety of the system in the efficiency of transportation [10]. However, despite the wireless sensors and WSN have numerous applications [11-13], only a few developmental studies have been conducted on monitoring the tower body and rod-shaped object, particularly for the system that monitors the running state of tower body.

According to the experimental data, the wireless monitoring system can monitor the tower body running state effectively and accurately. The wireless monitoring system consists of a MEMS-based three-axis acceleration unit, wireless network with wireless nodes and the monitoring server terminal. The wireless system combines a long-distance wireless communication module that transfers the data to the remote server with a short-range wireless communication module located at the measurement device. This method of wireless system has been used in existing wireless monitoring systems [14]. Finally, a series of experiments (such as comparing with the measuring angle, etc.) have been conducted to test the performance of the wireless monitoring system and analyzing the results.

2. MEMS-Based Acceleration Sensors

2.1. Measurement of tilt angle

In this study, a MEMS-based three-axis acceleration sensor is used to measure the tilt angle of tower body employing a method for calculating the tile based on the difference between the acceleration due to combination of gravity and other stresses and the acceleration due to gravity alone. The angle which is generated between the two accelerations corresponds to the slope of the sensor and the tile angle of the tower body.

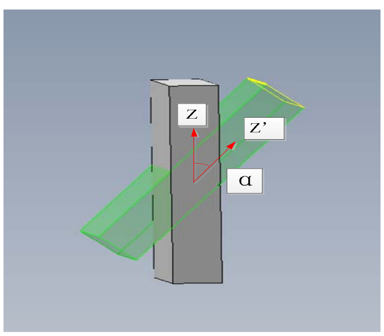


Figure 2: Tilt angle module

Figure 2 presents the change of three-axis accelerations when the module or the sensor deflects. The traditional method of tilt angle calculation [1] as the equations (1) and (2), where α denotes the slope of the sensors:

$$\alpha_x = g \cdot \sin\alpha \tag{1}$$

$$\alpha = \sin^{-1}(\alpha_x / g) \tag{2}$$

This study employs a new method to calculate the angle by six different accelerations (x, y, z, x', y', z'). The accelerations in two coordinates are deemed to be two different vectors $\vec{a}$ (x, y, z) and $\vec{b}$(x', y', z'), and the method of angle α calculation as the equations (3), (4), (5) and (6), where α denotes the slope of the sensors:

$$\vec{a} \bullet \vec{b} = x \cdot x' + y \cdot y' + z \cdot z' \tag{3}$$

$$|\vec{a}| = \sqrt{x^2 + y^2 + z^2}; \; |\vec{b}| = \sqrt{x'^2 + y'^2 + z'^2} \tag{4}$$

$$\cos\theta = \frac{\vec{a} \bullet \vec{b}}{|a| \cdot |b|} \tag{5}$$

$$\alpha = \cos^{-1}(\theta) \tag{6}$$

Using method of vectors to calculate angle has the advantage of installing the sensor nodes. When we install wireless sensor node onto the tower, we needn't to consider how to place nodes as the zero position, because we can set any position as a zero position by setting one of the vectors as the initial vector to calculate the angle.

2.2. Measurement of ice thickness on transmission line

With the low temperature environment in the wild, the transmission tower and line are under ice load. Transmission lines under the action of wind has simple harmonic motion, the empirical formulas of wind vibration frequency is $f = \frac{S \times v}{d}$; d is diameter of transmission line(mm) ,v is the wind speed(m/s), and S is the coefficient of Strouhal (S=200)[15]. According to the formula of simple harmonic motion, $w = 2\pi f$ and $\theta = wt$, we can have $\theta = 2\pi \frac{S \times v}{d} t$. So, if we get the wind speed, we can calculate the angle that is a deflection angle from suspension point under the action of wind.

This study measures the thickness of the ice with sensors and force analysis. The model of tower body and line is shown in Figure 3 without the action of wind. Through the analysis of the mechanics, we can get the mechanics equations.

$$F_1 \cdot \sin\theta_1 = F_2 \cdot \sin\theta_2 \tag{7}$$

$$F_1 \cdot \cos\theta_1 + F_2 \cos\theta_2 = F_T = mg \tag{8}$$

If the line is in the wind and makes the simple harmonic motion, we can analyze the cross section which is shown in Figure 4. We have the equations: $F_T \cos\theta = mg$ and $F_T \sin\theta = F_{wind}$, so we will get $\theta = 2\pi \frac{S \times v}{d} t$ and equation (9).

$$m = \frac{(F_1 \sin\theta_1 + F_2 \sin\theta_2)\cos\theta}{g} \tag{9}$$

$$h = \sqrt{\left(\frac{d}{2}\right)^2 + \frac{m - M}{\pi\rho}} - \frac{d}{2} \tag{10}$$

According to the equation (10) [16], we can get the Get the thickness of ice on transmission line, M is the weight of the transmission line in per unit length without ice, ρ is The density of ice(ρ =0.9g/cm3).

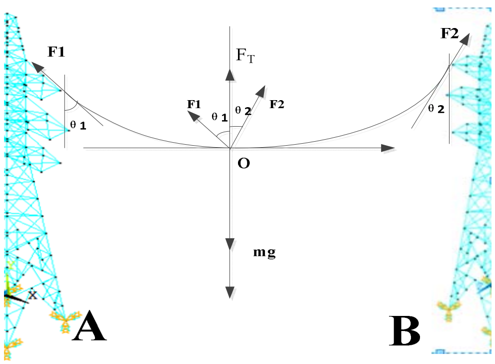


Figure 3: model of tower body and line

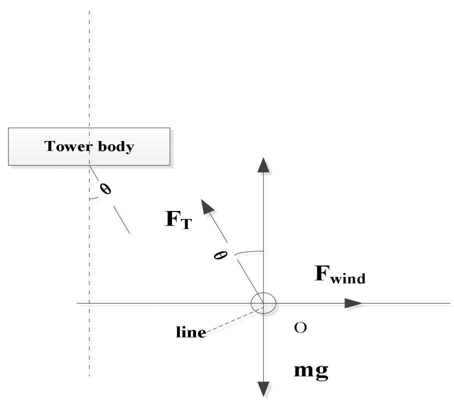


Figure 4: transmission line force analysis with wind

2.3. MEMS-based acceleration sensors—MMA8451

The MMA8415Q is a smart low-power, three-axis, capacitive (using spring quality system—the capacitance value will be changed when changing the gap between the mass and the fixed electrode during the quality affected by acceleration movement) micro-machined accelerometer with 14 bits of resolution. The MMA8451Q chip is made by Freescale Semiconductor. This accelerometer is packed with embedded functions with flexible user programmable options, configurable to two interrupt pins. This device can be configured to generate inertial wake-up interrupt signals from any combination of the configurable embedded functions allowing the MMA8451Q to monitor events and remain in a low power mode during periods of inactivity. The sensitivity is represented in counts/g. In 2g mode the sensitivity is 4096 counts/g, with a precision of 0.01°, the applicable temperature range is -40°C to +85°C, and thus, it is suitable for the monitoring for status of the tower body under harsh external conditions. The length and the width of the module are 20 mm and 14 mm, respectively.

Figure 5 shows application circuit of MMA8451Q, and the chip has I2C interface, we get the sensor data from two pins (SDA and SCL) through the I2C sequence which is shown in the Figure 6.

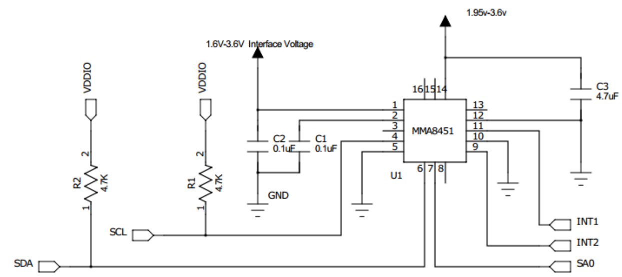


Figure 5: Application Circuit

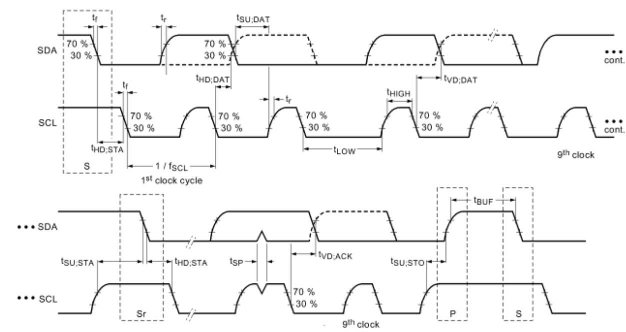


Figure 6: I2C slave timing diagram

3. Wireless Sensors Nodes and Network

The wireless node is an important part of the wireless system for monitoring the status of tower body and developed to transfer the data measured by the MEMS-based acceleration sensors wirelessly. In this study, the wireless sensor network consists of wireless sensor node and GSM (GPRS) module, the wireless system diagram is shown in Figure 7.

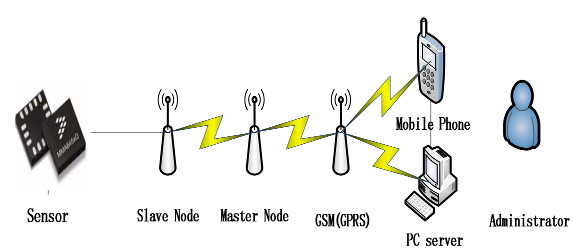


Figure 7: Wireless system diagram

The wireless sensor nodes refer to both the slave and master node. The slave node is consists of a MEMS-based three-axis acceleration sensor, CC2530 microprocessor and RF module (2.4-GHz radio frequency). RF waves are suitable for short-distance (30m—120m) wireless communication, make a connection between slave and master node and transmit the measured data. Sensors (such as accelerometer, temperature, humidity, etc.) are used to measure the status of the tower body, and according to the need can add other sensors, such as the wind speed sensor. With the deepening of the research, we can add temperature and humidity sensor, wind sensor and etc. A CC2530 chip [17] is used as the wireless data conversion device because this device can effectively convert an RF signal with low power and calculate data from the sensor. Figure 3 presents a diagram of the interior structure of the slave node. In the slave node, CC2530 controls the pulse signal to read the acceleration sensor data through the I2 C interface (SDA and SCL), and calculate to get tilt angle. The slave node transmits the angle to the master node. The board of the wireless slave node is shown in Figure 8 and Figure 9.

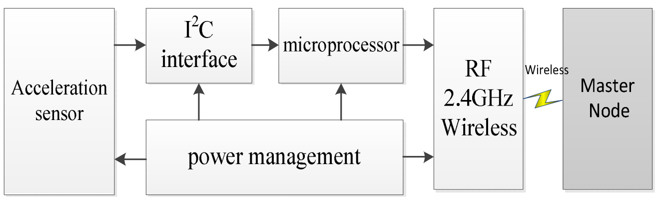


Figure 8: Slave node diagram

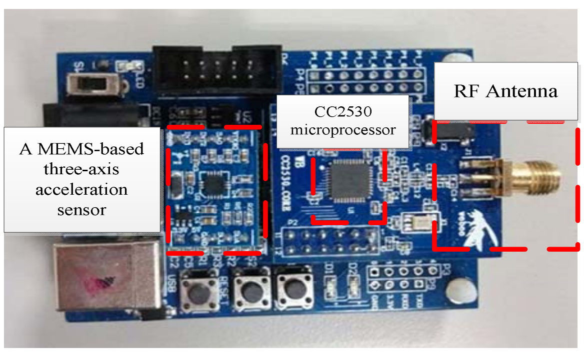


Figure 9: Slave node

The other wireless node is the master sensor node, receives the data transmitted wirelessly from the slave node and sends the angle data to the GSM (GPRS) module, and the module (TC35) sends data to mobile-phone or sever PC. Figure 4 presents the interior structure of the communication between master node and GSM (GPRS) module through RS-232. The board is shown in Figures 10-12.

For a wireless sensor, energy is usually provided from either solar power [18], structure vibration [19], chemical batteries or lithium batteries. In this study, during the experimental test phase, a lithium polymer battery is adopted, and provides electric power for the sensor, the slave, master wireless node and RF module. During the experiment, the low-power technology, such as the sleep mode, is not employed and the wireless nodes are operated continuously during testing. As the result of this, a lithium polymer battery can be uses 2-3 days during the experiment. However, in the practical application, the wireless sensor can run in the low power consumption mode by controlling the sleep timer in the CC2530 chip, and in this way can significantly extend the working life of the nodes. Because the biggest power component is CC2530 chip, when in the dormant state the power consumption of the node will be lower. In the low-power standby mode, 2 of number 5 dry cell can support 1 node to work 6~24 months. Recently, with the continuous development of the solar charging technology, the solar panels are applied in the wireless sensor network, and provide electric power more persistent for the wireless node.

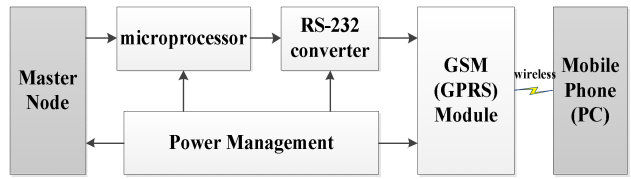


Figure 10: Master node diagram

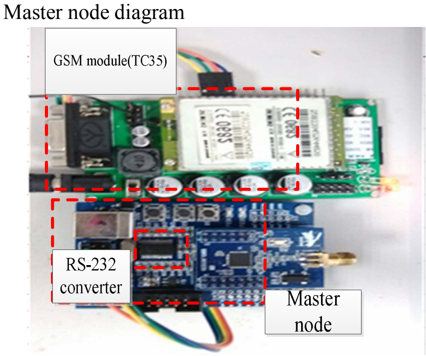


Figure 11: Master node and GSM (TC35)

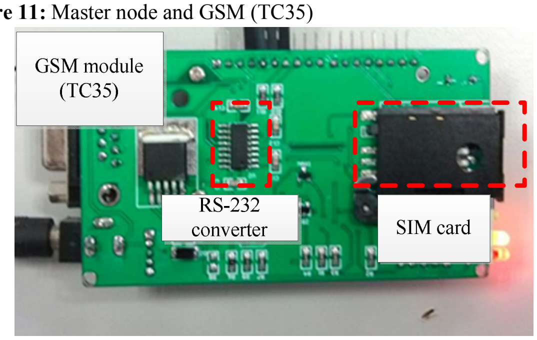


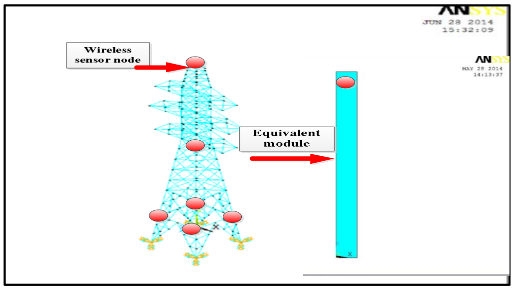
Figure 12: The bottom of GSM module (TC35)

4. Experiments

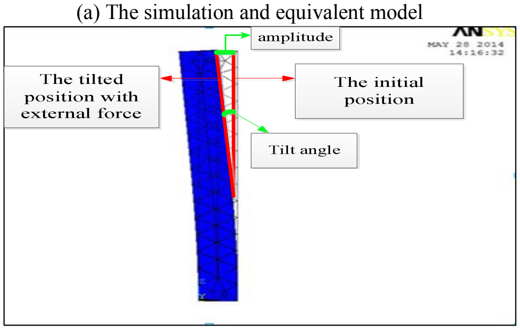
In order to verify the reliability and stability of the wireless monitoring system, this study conducted various experiments. The transmission tower is simulated using the finite element simulation software—ANSYS and equivalent to a rod body; comparing the wired and wireless method in transmission packet loss rate and etc.

4.1. Tower module and node installation

Figure 13 shows the simulation model and equivalent model, and in this study, fix wireless sensor nodes are installed on the tower. The slave node in the top of tower can react the tilt angle obviously. Amplitude can be calculated through the tilt angle and the equivalent model, and oscillation frequency can also be detected in per unit time with the tilt angle goes up and down.



(a) The simulation and equivalent model



(b) The tilt rod body analysis

Figure 13: Model analysis

4.2. Wireless packet loss detection

An experiment is designed to attain the transmission packet loss rate by comparing the wired and wireless transmission modes. The module structures are shown in Figure 14 and the result is shown in Figure 15. A salve node and a master node are connected with the PC through RS - 232 serial ports, respectively. Among them, a serial line transmits data from to PC directly and another one connecting with the master node. The master acquires data from slave node through ZigBee network, then sends to the PC through RS-232 serial port. According to the experiment, the wireless system has a low packet loss rate. That is, the monitoring center can receive most of the monitoring data with good reliability during the monitoring and analysis.

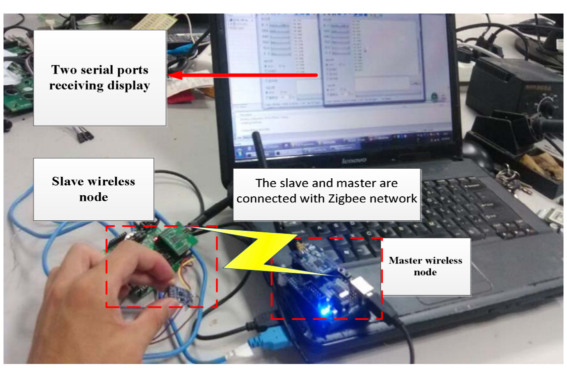


Figure 14: Module structures

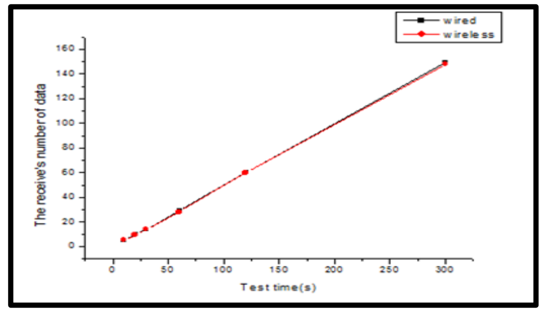


Figure 15: Result in 5 minutes

4.3. Accuracy test

To verify the accuracy, the tilt angle measured by the system is comparing with the protractor, as shown in Figure 16. It can be observed that the tilt angle measured from the system is close to the protractor and thus the method to obtain the tilt angle is accuracy. As the result shown in the Figure 17, another experiment is used to detect the fluctuation of the sensor when the angle of rotation is fixed. In the experiment, the sensor is fixed at an angle unchanged. The maximum sampling rate of the sensor is 1024Hz .When working at low power, the sampling rate is 16Hz. The reference position is determined when the sensor is installed.

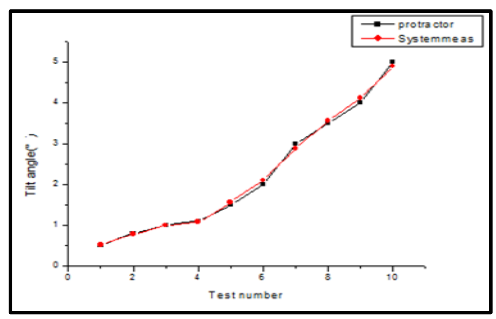


Figure 16: Accuracy test

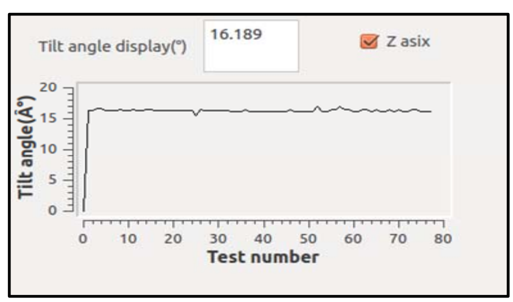


Figure 17: Fixed point of the test

4.4. User interface

The User interface is shown in Figure 18, which displays the parameters and functions of the system. In the sever PC, the received data is stored in a database, and the administrator can view the data using the interface, and set the system parameter.

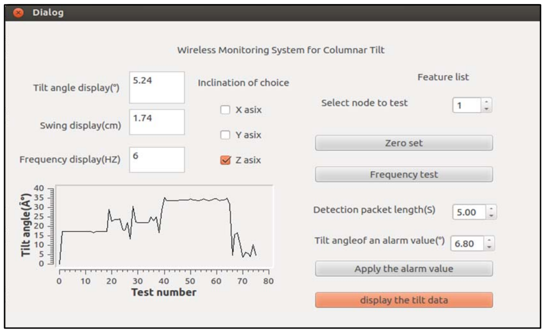


Figure 18: User interface

5. Conclusion

A wireless system for monitoring the status of tower body, which consists of MEMS-based acceleration sensor, slave and master wireless nodes, and GSM (GPRS) module, was presented. Experiments were conducted to validate the system. Some conclusions can be drawn as follows:

1) Based on the SHM and WSN technologies, a wireless system is designed to monitor the status of tower body.
2) Using a novel method of vector dot product to calculate the angle, the problem of setting the initial position was solved.
3) The wireless system consists of a long-distance wireless communication module that transfers the data to the remote server and a short-range wireless communication module that includes slave nodes and a master node. The slave node with the sensor transmits the angle to the master through ZigBee network in a short-distance, while the master sends the angle data to the GSM (GPRS) module for transmitting the angle to the sever PC or a mobile phone in a long-distance.
4) The accuracy, stability and reliability of the wireless system were verified in several laboratory tests.

6. Acknowledgement

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7. References

[1] Tang L, Zhang K, Chen S, et al. MEMS inclinometer based on a novel piezoresistor structure [J]. Microelectronics Journal, 2009, 40(1): 78-82.

[2] Ho Jung, Chang Jin Kim and Seong Ho Kong, "A MEMS-Based Electrolytic Tilt Sensor," IEEE SENSORS, pp. 1199–1202, Oct. 2007.

[3] Luczak S, Oleksiuk W, Bodnicki M. Sensing tilt with MEMS accelerometers [J]. Sensors Journal, IEEE, 2006, 6(6): 1669-1675.

[4] Y. Yu, "Wireless sensors and their networks for structural health monitoring," Ph.D. dissertation, Harbin Inst. Technol., Harbin, China, 2006.

[5] S. Glaser, H. Li, M. Wang, J. Ou, and J. Lynch, "Sensor technology innovation for the advancement of structural health monitoring: A strategic program plan of US–China research for the next decade," Smart Struct. Syst., vol. 3, no. 2, pp. 221–244, 2007.

[6] M. Saafi and P. Romine, "Embedded MEMS for health monitoring and management of civil infrastructure," Proc. SPIE—Int. Soc. Opt. Eng., vol. 5391, pp. 331–343, 2004

[7] Ha D W, Park H S, Choi S W, et al. A Wireless MEMS-Based Inclinometer Sensor Node for Structural Health Monitoring[J]. Sensors, 2013, 13(12): 16090-16104.

[8] Zhu Y, Xie L, Yuan T. Monitoring system for forest fire based on wireless sensor network[C]//Intelligent Control and Automation (WCICA), 2012 10th World Congress on. IEEE, 2012: 4245-4248.

[9] Jang S, Dahal S, Contreras G K, et al. Hybrid structural health monitoring for in-service highway bridges using wireless multiscale sensors[C]//SPIE Smart Structures and Materials+ Nondestructive Evaluation and Health Monitoring. International Society for Optics and Photonics, 2012: 83451Y-83451Y-6.

[10] Chan A C K, Okochi S, Higuchi K, et al. Low power wireless sensor node for human centered transportation system[C]//Systems, Man, and Cybernetics (SMC), 2012 IEEE International Conference on. IEEE, 2012: 1542-1545.

[11] Lee H M, Kim J M, Sho K, et al. A wireless vibrating wire sensor node for continuous structural health monitoring [J]. Smart Materials and Structures, 2010, 19(5): 055004.

[12] Xu N, Rangwala S, Chintalapudi K K, et al. A wireless sensor network for structural monitoring[C]//Proceedings of the 2nd international conference on Embedded networked sensor systems. ACM, 2004: 13-24.

[13] Kim S, Pakzad S, Culler D, et al. Health monitoring of civil infrastructures using wireless sensor networks[C]//Information Processing in Sensor Networks, 2007. IPSN 2007. 6th International Symposium on. IEEE, 2007: 254-263.

[14] Sung W T, Hsu C C. Intelligent environment monitoring system based on Innovative Integration Technology via Programmable System on Chip platform and ZigBee network [J]. IET Communications, 2013, 7(16): 1789-1801.

[15] TANG Xiaoyou. The oscillating mechanism of conductor galloping at the low-damping resonance [J]. Journal of Northeast Dianli University: Natural Science Edition, 2006, 26(1):65-70.

[16] ZHANG Yu. On-line monitoring system of overhead electrical power lines icing [J]. High Voltage Engineering, 2008, 34(9):1992-1995.

[17] Texas Instruments. Data Sheet for CC2530. Available online: http://www.ti.com/product/CC2530 (accessed on 14 June2014).

[18] Kohvakka M, Hannikainen M, Hamalainen T D. Wireless sensor prototype platform[C]//Industrial Electronics Society, 2003. IECON'03. The 29th Annual Conference of the IEEE. IEEE, 2003, 2: 1499-1504.

[19] Meninger S, Mur-Miranda J O, Amirtharajah R, et al. Vibration-to-electric energy conversion[J]. Very Large Scale Integration (VLSI) Systems, IEEE Transactions on, 2001, 9(1): 64-76.