www.s2is.org
International Journal on Smart Sensing and Intelligent Systems
ISSN 1178-5608

BRIDGE DEFLECTION MEASUREMENT USING WIRELESS MEMS INCLINATION SENSOR SYSTEMS

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Submitted: Sep. 17, 2012 Accepted: Jan. 10, 2013 Published: Feb. 20, 2013

Abstract- Bridge is an important part of modern transportation systems and deflection is an important index for bridge's safety evaluation. In this paper, a method of deflection measurement using Wireless MEMS Inclination Sensor Systems (WMISS) is presented and validated. Firstly, based on various bridge deflection measuring methods, the method of deflection measurement using inclination parameter is introduced. Secondly, a low-power wireless inclination sensor based on 3D-MEMS SCA60 inclinometer is designed using modularization way, and this kind of wireless sensor loaded with ZigBee/IEEE 802.15.4 MAC protocol stack can self-organize wireless sensor network, measure the

angle value and send the data to the coordinator. Then the deflection curve is displayed on PC. Finally, deflection measurement experiments are conducted on a bridge model and Beida Bridge. The experimental results show that, the presented deflection measurement method is feasible, practical and reliable; the wireless inclination sensor is easy to operate with no lines, and has extensive and broad application prospects.

Index terms*:* wireless sensor networks, MEMS, deflection measurement, inclination, bridge

I. INTRODUCTION

Bridge is an important component of modern transportation systems. With the rapid development of national economy, transportation industry in China is booming, which puts forward higher requirement on the safety of bridge structure. Therefore, safety monitoring is quite necessary. As science and technology develops, an increasing number of devices are used on bridge monitoring. Through the analysis of the collected data, people can get knowledge of working conditions of bridges not only in the past, but also in the future. During this process, deflection is essential. Deflection is the key technical parameter that judges the vertical stiffness, load-bearing capacity, and integrality of the bridge. Moreover, it is an important index of bridge detection. Bridges whose deflections overpass the specified limit of design may increase damage accumulation and even collapse at any time, which pose a serious threat to people's lives, and bring about a great loss of property. Therefore, monitoring the deflections of bridges is indispensable.

In recent years, the number of methods of measuring bridge deflection has been increasing. For example, measuring the deflection using robot, which has characteristics of high intelligence, fast measuring speed, large measuring range, high accuracy, and high cost. Another method of measuring deflection is to take advantage of the photoelectric level of communicating tubes. Although it has high precision, it is not that easy to implement it because the needed objective cursor is difficultly decided in practical measurement. A third method is that loading stretching wires uses displacement sensor to measure deflection. A fourth method is GPS deflection measurement, in which the precision is the rate of "cm" and the system is expensive. In addition, there is a method of non-contact optoelectronic measurement based on image processing technology. Affected by these factors, such as various structures, wide range, huge load, complex enforced situation, etc, it is necessary to make detailed analysis for different conditions when the deflection is being measured. In order to adopt methods suitable for the bridge itself to complete the deflection measurement, further research should be conducted based on the basic principle, performance and bridge type. And for most deflection measurement methods, sensor is integrated into the measurement system by line, which is not convenient for practical engineering. Fortunately, wireless sensor network technique has been developing rapidly, and is being used gradually in Structural Health Monitoring for civil engineering structures in an attempt to lower the high capital costs and rapid installation associated with wire-based structural monitoring systems [1-5].

Based on the above, wireless inclination deflection measurement is discussed in this paper. A kind of wireless inclination sensor is designed. Detailed description has been given on hardware design, software design, system integration, and actual tests.

II. REQUIREMENT OF A CURRENT LIMITER

a. Comparison of current deflection measurement methods

a.i Robot deflection measurement

Surveying robot is a kind of intelligent measurement instrument, which can automatically search, lock accurately target, and thus record angle, distance, coordinates and image information. The robot integrates optoelectronics ranging system, electronic measuring angle system, servo motor drive system, the CCD image sensor, ATR (automatic target recognition) mechanism. Robot deflection measurement is done by the following steps: First, prism is mounted on the bridge, and then surveying robot collects geometry information of the prism by measuring robot in loading respectively before and after the bridge is loaded, finally the corresponding deflection value is calculated [6].

a.ii Laser image deflection measurement

Laser image deflection measurement is realized by means of the good directionality of laser. The laser fixed on the bridge creates a laser spot on the stationary optoelectronic receiver, whose center moves equivalently as the bridge distorts at different levels. Therefore, bridge deflection is available as long as the spot center is obtained. When used on deflection measurement, laser image method is of high-accuracy, which can achieve 0.1mm. Besides, its high sampling rate and low cost are also suitable for bridges of small and medium size [7].

a.iii GPS deflection measurement

As a generation of satellite navigation and positioning system, GPS (global position system) has not only global, 24-hour, continuous and precise three-dimensional navigating and positioning capabilities, but also a good anti-interference and confidentiality. In recent years, precise positioning technology using GPS on large-span bridge monitoring has drawn wide concern, and there have already been many examples of successful applications. Its basic principle is: one receiver (base station) is fixed on the reference point and the other (mobile station) is located where the most distortion occurs on the bridge, so that both of them can observe more than 4 satellites simultaneously to determine the relative location of the deformation point. Through real time acquisition of the relative position of the deformation point to the reference point, which directly reflects the special change of the measured point, the deflection of the bridge structure can be obtained [8].

a.iv Robot deflection measurement

Using the principle of connecting pipe, the change of bridge deflection can be acquired according to the liquid level heights in the connecting pipes that are located on various points of the bridge. In the measuring process, a horizontal pipe should be set along the bridge. On the other hand, vertical pipes, in which liquid levels maintain the same, are located on the monitoring points which are also connected with the horizontal one. One vertical pipe has to be set on the shore base, so that the liquid level in it can be taken as the reference for monitoring. When there is deformation of the bridge beam, the pipes fixed on it will move together, which can result in various degrees of changes of the liquid levels in them, although the liquid surfaces in all the vertical pipes still keep horizontal. The relative displacements obtained in this way are the deflection values of the measured points [9].

a.v Electro-optical imaging deflection measurement

Electro-optical imaging deflection measurement is the way in which a target with an optical point (cursor) on it should be set on the measured point of the bridge. Then the image of the optical point will be formed on the CCD receiving area-array through the optical system (optical lens). When there is deflection/displacement of the bridge, the target will shift position. To measure the variation of the imaging position of the optical point on the CCD and the practical deflection/displacement value of the bridge could be calculated [10].

a.vi Inclination deflection measurement

Free from the confinement of the site condition such as sunshine, rain, fog and etc, inclination deflection measurement of bridge deflection monitoring has large measuring range and is capable to complete one/two-dimensional measurement, which is suitable for deflection measurement of large/medium-size bridges. Yang and others took advantage of QY inclinometer to conduct the measurement of static-load deflection on the Songhua River Railway Bridge in Harbin and the Jiujiang Rail Road Bridge, achieving satisfactory results [11].

Table 1: Shows the comparison of the above deflection measurement methods

Deflection Measurement Methods	**Precision**	**Dynamic / Static measurement**	**For bridge-type**	**Cost**
Inclination	below cm	Dynamic / Static	Large rigid-frame bridge	common
GPS	cm	Static	large-scale bridge	expensive
Laser imaging	below mm	Dynamic / Static	Medium or small-scale bridge	expensive
Connection pipe	below mm	Static	any	general
Electro-optical imaging	cm/mm	Dynamic / Static	large-scale bridge	More expensive

b. Deflection Measurement Using Inclination Method

b.i Principle

Take simply-supported beam (shown in Figure 1) as the example to work out the relationship between load and deflection using mechanics of materials, this derivation is based on Euler-Bernoulli beam theory (i.e. shear deformation is neglected). Since there is a linear relationship between beam deflection and loads, which obeys Hooke's Elasticity Law whose coefficients are related to the stiffness characteristics of the material. The deformation of the beam caused by each load is unconnected, satisfying the superposition law. Thus the loads can be separated and the deflection caused by every single load can be calculated.

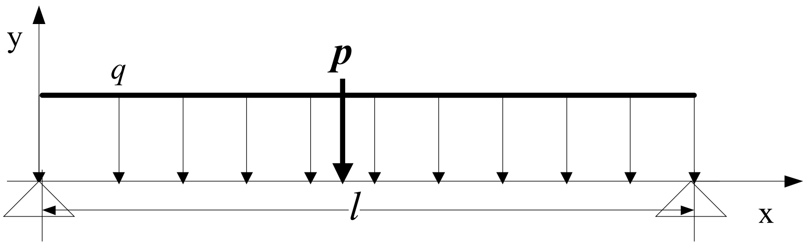

Figure 1. Mechanics model of simply-supported bean

Without external load, only gravity loads of the beam itself should be considered and these loads are uniformly distributed within the whole length of the beam. Suppose the density of the loads is q (*N/m*) and the length of the beam is l. Then set up a suitable coordinate system and use mechanics of materials to derive the equation which can be applied to any point of the beam, the angle " θ "equation is shown below:

$$\theta = y' = -\frac{q}{24EI}(l^3 - 6lx^2 + 4x^3) \qquad (1)$$

EI is a constant, which indicates flexural rigidity of the beam. E is extension-compression elastic modulus and I is moment of inertia. The deflection value of any point of the beam can be calculated. And the deflection curve "y" equation is:

$$y = -\frac{qx}{24EI}(l^3 - 2lx^2 + x^3) \qquad (2)$$

The following equations can be obtained from the above ones， Equation 3b is used to get on the central point of the beam.

$$\theta_{\max} = \pm \frac{ql^3}{24EI} \quad \text{and} \quad y_{\max} = y\,|_{x=\frac{l}{2}} = \frac{5ql^4}{384EI} \tag{3a,b}$$

Now, the deflection of the bridge is analyzed when only external loads are considered. External loads are generally applied by vehicles traveling on the bridge. Deflection caused by vehicles is much lighter than that caused by bridge gravity. As for the simply-supported bridges, the key point should be focused on the deflection of bridge center. Therefore, the model can be simplified to carry out the calculation after concentrating the loads on the central point. When external loads *P* are all applied on the center, namely, $x=l/2$, the deflection caused by them is:

$$y(x) = -\frac{px}{12EI}\left(\frac{3l^2}{4} - x^2\right) \quad 0 \le x \le \frac{l}{2} \ ,$$

$$y(x) = -\frac{p}{12EI}\left(x^3 + \frac{9l^2x}{4} - 3lx^2 - \frac{l^3}{4}\right) \quad \frac{l}{2} \le x \le l \tag{4a, b}$$

According to the superposition principle, the curve equation of the deflection caused by bridge gravity and external loads is:

$$y(x) = -\frac{px}{12EI}\left(\frac{3l^2}{4} - x^2\right) - \frac{qx}{24EI}\left(l^3 - 2lx^2 + x^3\right) \qquad 0 \le x \le \frac{l}{2},$$

$$y(x) = -\frac{p}{12EI}\left(x^3 + \frac{9l^2x}{4} - 3lx^2 - \frac{l^3}{4}\right) - \frac{qx}{24EI}\left(l^3 - 2lx^2 + x^3\right) \quad \frac{l}{2} \le x \le l \tag{5a, b}$$

The curve reaches its peak on the central point:

$$y_{\max} = -\frac{l^3}{48EI}\left(p + \frac{5ql}{8}\right) \tag{6}$$

From the above equations, it is known that the unknown parameters *EI* of the deflection curve can be calculated through measuring the slope of the curve, which is angle value. Then, the deflection curve equation and the deflection of any point are all obtained.

b.ii Implementation of Inclination Deflection Measurement

(1) Single-point Method

In the condition of simple-supported beam without external loads, it can be observed from the equations above that the angle equation will be obtained through derivation of the deflection one.

After measuring inclination, the values of the unknown parameters can be got through using its relationship with inclination, and then the deflection value will be obtained.

(2) Double-point Method

In the condition of simple-supported beam with external loads, the curve of the deflection is presented by equation (5a, b).

Considering $\frac{p}{12EI}=a$, $\frac{q}{24EI}=b$, and conducting the substitution on the above equations(5a,b) to get angle equations(7a,b) , the value of *a* and *b*, obtained by putting measured angle value into the equation (7a, b), are input the equation 6 so that deflection value can be obtained. This method can be applied to the measurements of other points by means of least square method.

$$y'(x)=(3x^2-\frac{3l^2}{4})a+(6lx^2-l^3-4x^3)b \quad 0\le x\le\frac{l}{2} ,$$

$$y'(x)=(-3x^2-\frac{9l^2}{4}+6lx)a+(-l^3+6lx^2-4x^3)b \quad \frac{l}{2}\le x\le l \qquad (7a, b)$$

III. DESIGN OF WMISS

WMISS consists of wireless inclination sensor nodes and one coordinator connected to a PC through the serial port. Wireless inclination sensor node is a low power one which completes the wireless transmission of inclination data through wireless sensor network to achieve the deflection measurement. The coordinator can finish the functions such as building networks, receiving and transmitting the data. The same embedded program is preloaded into the wireless inclination sensor nodes. At the same time, the Labview program is running to work out deflection on the PC, the structure of the system is shown in Fig. 2.

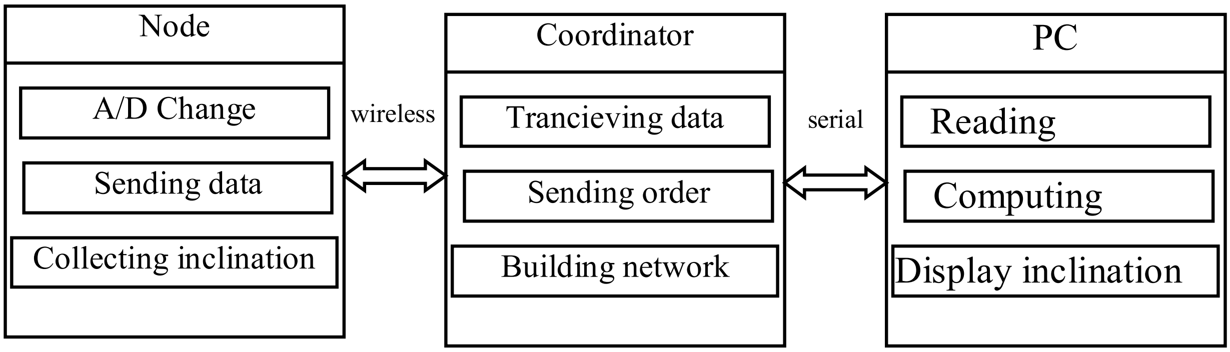

Figure 2. Structure of WMISS

a. Hardware Design

Wireless inclination sensor node is developed by the way of module design [12-16], as is shown in Fig. 3. It consists of inclination sensor based on 3D-MEMS SCA60, micro-process module MSP430, wireless module cc2520&2591, power module, etc. The coordinator is composed of micro-process module, wireless module, power module and serial port module.

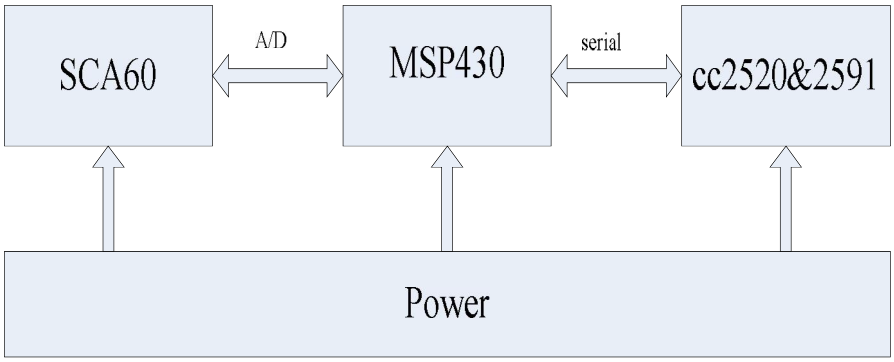

Figure 3. Modules of wireless inclination sensor node

a.i MEMS SCA60 inclinometer

The SCA60 Series is a 3D-MEMS-based [17] single axis inclinometer family that provides instrumentation grade performance for leveling applications. Low temperature dependency, high resolution and low noise, together a with robust sensing element design, make the SCA60 the ideal choice for leveling instruments. The inclinometers are insensitive to vibration, due to their over damped sensing elements, and can withstand mechanical shocks of up to 20000 g. SCA60 chip, with a surface micromachined polysilicon structure built on top of a silicon wafer, is a digital sensor shown in Figure 4. The chips are mounted on a lead-frame and wire bonded to appropriate contacts. The encapsulation process is a standard semiconductor transfer molding process. It is mainly made up of a sensing elements and an ASIC circuit, the sensing element is actually silicon sensing differential capacitive accelerometer responding to gravity according to its orientation, and the ASIC, integrating EEPROM memory, amplifier, analog/digital converter, temperature meter and serial peripheral interface (SPI), is used for finishing temperature compensation and digital disposal of sensing elements' outputs. The inclination is an angle between gravity and the sensor, the relation of the output of acceleration and gravity is given in the equation 8,

$$a_x = g * \sin\alpha \qquad (8)$$

Where, a_x is the output of acceleration, g is gravity, α is inclination angle. Equation 8 is changed into equation 9 by inverse sine to get the inclination value. And the temperature compensation using internal temperature sensor makes inclination measure more precisely.

$$\alpha = \sin^{-1}(a_x / g) \qquad (9)$$

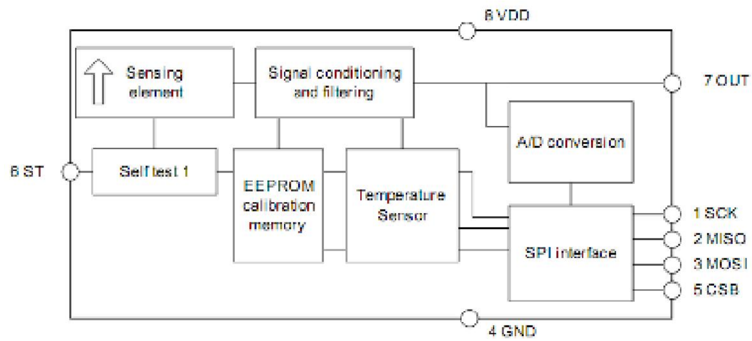

Figure 4. Functional blocks [18]

a.ii Wireless inclination sensor

In this design, processor module is an MSP430F5438 single chip, which has a 256KB flash and a 16KB RAM; wireless module consists of a CC2520 wireless radio frequency chip and a front-end amplifier CC2591. The CC2520 wireless radio chip, produced by TI Company, is the second generation ZigBee/IEEE 802.15.4 wireless radio transceiver of 2.4 GHz. The CC2591 is a radio front-end of highest integration rate facing low power and low voltage, which can improve the power of transmitter and the sensitivity of receiver, so that the strength and the transmission distance of the wireless signal increases. Power module is a Max8569 DC Boost Chip of 3.3V and 5V. The sensor nodes designed are shown in Figure 5.

Figure 5. Wireless inclination sensor node

b. Software Design

The software of WMISS consists of two parts: the embedded program loaded on the wireless sensor node and the upper PC program.

b.i Sensor node program

The software is developed on the basis of IEEE 802.15.4 MAC protocol. In charge of the IEEE 802.15.4 group, the LR-WPAN Design of IEEE 802.15.4 MAC Protocol aims at low cost and low power, also realizes the functions of establishment, maintenance, confirming the sending and receiving of frame, channel access control, frame check, etc. In addition, it provides service interface of point-to-point communication for the visits to physical channels from high layer. The association, disassociation and orphan notification mechanisms provided by it have effectively solved the problem of getting in and out of the network of the nodes. Meanwhile it has improved the organizing and self-healing abilities [19].

After the sensor node is powered on, the channel will be monitored so as to judge whether there is a coordinator in that area. If there is, start it as a terminal node; otherwise, start it as a coordinator. Then the network will be set up. In this paper, the network construction of anchor-free and unslotted CSMA-CA competitive mode has been discussed (shown in Figure 6).

Terminal node sends out net access application to coordinator, and coordinator gives response to it by sending responding-frame. When the network is successfully constructed, connection between nodes and coordinator will be built up, after which nodes could compete for channel in the way of unslotted CSMA-CA competitive mode. When there is a confliction, circumvention will be made according to the CSMA-CA algorithm. Then the data will be resent. In order to obtain the ID numbers and AD values of inclination of the nodes, the coordinator makes analysis after receiving the data. Then it will put them into the buffer zone and send them out.

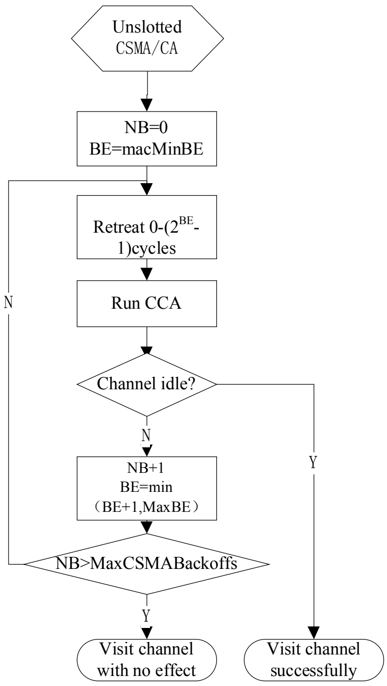

Figure 6. Flow chart of unslotted CSMA-CA

b.ii Program of upper computer based on Labview

The software of upper computer（PC in Fig.2） is realized in Labview:

(1) Configure the parameters of the serial port and initialize;
(2) Use the control to monitor the serial port and read data from it. Separate the character string into two parts (ID number and inclination value);
(3) Transform the inclination data into corresponding inclination value and calculate the deflection according to the theories of Material Mechanics;

(4) Display the deflection curve and deposit the data into files.

Figure 7 shows the flow chart of program on PC, and Figure 8 gives the interface of deflection measurement based on Labview.

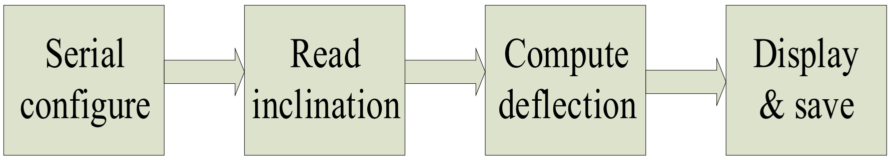

Figure 7. Flow chart of program on PC

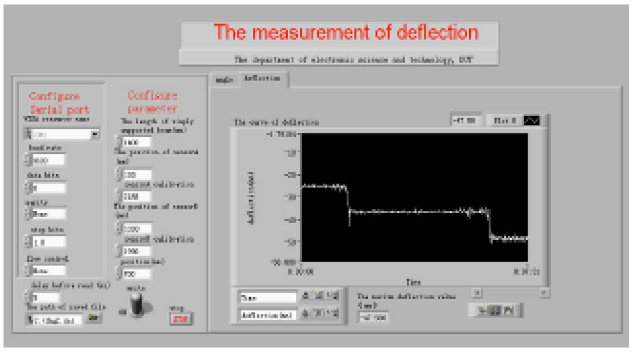

Figure 8. Wireless deflection measurement program based on Labview

IV. EXPERIMENTS AND DISCUSSIONS

a. Calibration Experiment

As shown in Fig. 9, the experimental emulation devices consist of a MSP430 simulator of USB type, a wireless sensor board, serial port cables, a power module, etc. After wireless sensor board is powered on, the channel will be monitored with the yellow light flickering fast. When the key on the right is pressed, the yellow light will stop flickering and the coordinator will start, so that the network could be established. Then the other sensor board will be powered on with the yellow light flickering. After pressing the right key, the yellow light flickers slower, which indicate that the node has received the acknowledgement frame and joined the network. Press the left key, so that data can be sent to the coordinator. The flickering of the red light on the coordinator shows that the data has been received. Then data will be transferred from a serial port to PC, read by Labview, processed and shown as deflection curves. The display interface of deflection curves based on Labview is concise and easy to operate. Through tests, it is proved that the transmission distance can achieve 250 meters.

Figure 9. Experimental emulation equipments

Wireless deflection measurement is done on the bridge model shown in Figure 10. The bridge model is loaded gradually in the rate of 1 kg. Wireless inclination sensor is put on the bridge model to measure the change of the deflection when the loads on it are increasing. Experimental results are shown in Figure 11. The laser displacement sensor method is used for a standard to compare with wireless inclination sensor one, the deflection is used as true value. The experimental results show that the error between the two methods is no more than 3%, so the wireless inclination sensor method is in accordance with the laser displacement sensor one.

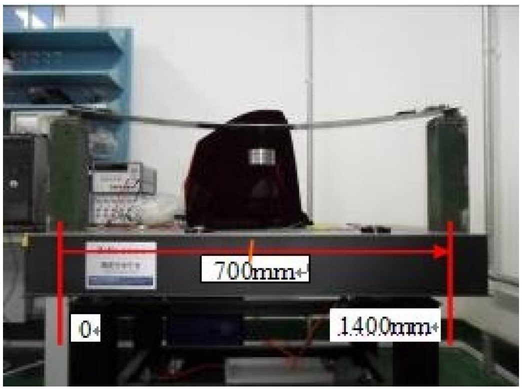

Figure 10. Bridge model for deflection measurement

And errors include random error and system error. It is to reduce the random error of measurement results to use the measured value averaged method. Correlation analysis of system error can identify impact factor of measurement results, and thus fix deflection measurement result. It is also to improve the accuracy of measurement deflection by changing the configuration of the wireless inclination sensor. In addition, it is to reduce the relative error of measured deflection by amending the deflection calculation algorithm using inclination.

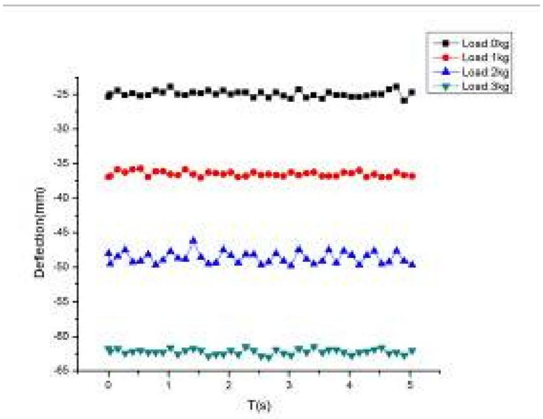

Figure 11. Experimental results with loading

b. Field Measurement

b.i Beida Bridge

Beida Bridge, located in the Tiger Beach of Dalian City, is a traffic hub of southern coastal scenic spots of Dalian, shown in Figure 12. The bridge is a three-spans and simply-supported reinforced suspension bridge, main span is about 132 meters, both side span is about 48 meters, steel bridge tower is made up of the ordinary No. 3 carbon steel, tower is 35 m high. The whole bridge is 230 meters in length, 12 meters in width. Main cable, 132 meters sagittal high, is made up of 37 wire ropes with 42mm. The bridge has been in-service for about 20 years, and the protection technology of the bridge is relatively backward, bridge section structure appears rustily, the bridge's current operating condition is concerned. According to the nearby residents reflected, people can feel bridge body vibrates up and down significantly while vehicle across the bridge. Therefore, in order to ensure the safe operation of the bridge, it is necessary to measure, validate, and repair the bridge. Based on this, the vertical deflection of the bridge's mid-span is measured using WMISS.

Figure 12. Beida Bridge

b.i Measurement

Two wireless inclination sensors conducted a zero calibration are respectively put both sides of Beida Bridge's midspan. The coordinator and wireless sensor nodes are powered on, the wireless sensor networks is built using the embedded software, and then the deflection measurement using WMISS is conducted while there are three buses and some cars across the bridge. The sensor collocation is shown in Figure 13. Deflection measurement result is shown in Figure 14. With two sides fulcrum for reference point, the maximum midspan deflection is up to 248.49 *mm*, while the value in 2005 is 195 *mm* and the value in 1995 is 181 mm [20], all these show that the current deflection of the bridge's midspan is larger. The large deflection's change not only directly influences the bearing capacity of the bridge, but also reduces the driving comfort. The bridge, with an obvious shock while in a large deflection, makes people produce a kind of not safe feeling. On the basis of measurement result using WMISS, it is necessary to repair the Beida Bridge, especially its suspension cable, in order to prevent the deflection from increasing. Now Beida Bridge's operation is good after maintenance.

Figure 13. Sensor collocation

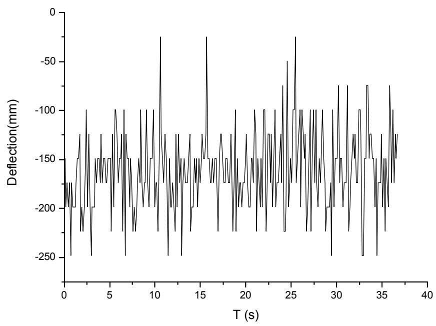

Figure 14. Deflection measurement using WMISS

V. CONCLUSIONS

In this paper, a measurement method of deflection using self-designed WMISS is introduced. By means of measuring inclination and applying mechanics of material, the deflection of structure can be calculated. The wireless inclination sensor is calibrated on the bridge model to accomplish the data collection using the MAC Protocol provided by TI Company. The WMISS is applied for deflection measurement of Beida Bridge of Dalian city, and present the repair project of the bridge according to the analysis of the measured data. The wireless sensor in this method are simple and easy to operate, and of high applicability. It represents an important direction for the development of bridge deflection measurement, which has extensive applicability and broad application prospects.

In general, the design is preliminary and further improvement is necessary. More importantly, more tests need to be carried out before it can be of practical use.

VI. ACKNOWLEGEMENT

Financial supports for this study is provided by grants from the National Nature Science Foundation of China (Project No.51108060,51161120359,50921001), The natural science foundation of Liaoning Province (201202039), the 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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