

Wireless Sensor Network Based Cable Tension Monitoring for Cable-stayed Bridges

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Abstract—Cable tension force is one of the most important criteria for assessing the work condition of a cable-stayed bridge. As a result, it is necessary to be monitored during operation. Rapid development of wireless sensor network (WSN) technology makes it possible to realize cable tension monitoring conveniently. In this paper, a wireless sensor network based monitoring system was proposed for cable tension force measurement of a cable-stayed bridge. In order to verify the feasibility and reliability of the proposed system, laboratory experiments were conducted at first. Two different wires with diameter of 5mm and 7mm respectively and with different lengths were tensioned to different force levels to simulate different cases. Then, the monitoring system was deployed on Ronghu Bridge, a cable-stayed bridge in Wuxi, Jiangsu Province, China. According to experimental results and field measurements, the difference between the measured cable tension forces and the design values is less than 5%.

Keywords—Cable-Stayed Bridge, Structural Health Monitoring, Wireless Sensor Network, Tightening String Model, Vibration Frequency Method.

I. INTRODUCTION

Cable tension force is one of the most important criteria for assessing the work condition of a cable-stayed bridge. As a result, it is necessary to be monitored during operation. The available methods generally employed for measuring the cable tension force for cable-stayed bridge include: oil pressure meter method, pressure transducer method and vibration frequency method [1]. The first two methods measure the cable tension force by directly applying an inversed tension force to the cable with the cable anchor plate as the reaction support. The inversed tension force is increased till the anchor of the cable separates from the reaction plate. Then the applied tension force is measured using an oil pressure meter or a pressure transducer alternatively. These methods are very straight forward but need dedicated and expensive devices and quite difficult after a cable-stayed bridge has been in use. These methods are generally used during the construction stage of a cable-staged bridge.

Vibration frequency method is an indirect method which measures the dynamic response of a cable firstly. From the dynamic response induced by ambient vibrations, natural frequencies of a tension cable can be extracted and its tension force can be computed based on cable vibration theory. This method has been widely used in recent years [2].

Traditionally, dynamic response of a tension cable is measured by wired systems. As they use cables to connect sensors to data acquisition loggers, it is difficult and time-consuming to install and maintain. This makes wired system too expensive to popularize. At the other hand, the wired system is not flexible so addition or adjustment of sensors is painful. Rapid development of wireless sensor network technology makes it possible to realize cable tension monitoring conveniently. For the shortcomings of traditional wired systems, a wireless sensor network based monitoring system has been proposed in this paper. The proposed system is verified comprehensively through laboratory experiments and field deployments. It is shown that the proposed system can monitor cable tension force precisely.

The rest of this paper is organized as follows. In Section II, related works of cable tension force monitoring are discussed. In Section III, the wireless sensor platform for vibration measurement and analytical model used to compute cable tension force are briefly described. In Section IV, laboratory experiments and results are given. In Section V, field deployment and verification are explained. We conclude this paper in Section VI.

II. RELATED WORKS

Wireless sensor networks have been used for several short-term structural assessment projects

[3]-[5]. In these works, vibration response of bridges is sampled and analysed. However, as the targeted bridges are not cable-stayed, there is no cable tension force monitoring included.

References [6]-[9] use wireless sensors to monitor cable tension force. Soojin Cho et al [6]-[7] developed a low-cost wireless tension force estimation system and tested it with a laboratory cable in different cases. Detailed algorithms for computing cable tension force from measured vibration response are presented. However, there is no field deployment on real bridges for this system. G. Feltrin et al [8]-[9] deployed wireless sensors on cables of a cable-stayed bridge in Switzerland. However, there is no experimental verification for their system and only measured natural frequencies are presented. Without comparison with design values or measured values using traditional methods, it is impossible to validate its feasibility.

The Jindo bridge project directed by B. F. Spencer Jr. [10]-[11] gives the most similar work with ours. They deployed wireless sensors to monitor cable tension force of a cable-stayed bridge. The measured results are compared with design values and measured values using traditional methods. However, different algorithms for computing cable tension force are used but approximate error performance is obtained.

III. WIRELESS SENSOR PLATFORM AND ANALYTICAL MODEL

A. Wireless Sensor Platform

The vibration response of cables has the characteristics of low frequency and low amplitude. In order to measure such low frequency weak signals, the sensor should have high sensitive and good low frequency response.

In our sensor platform, we chose SD1221 [13], a MEMS accelerometer, to measure vibration. We designed a data acquisition board to gather data from SD1221. The board is interfaced with Micaz node which controls data acquisition and transmits acquired data to sink nodes. The data acquisition board has three independent channels which can connect three SD1221 to provide three-dimensional acceleration measurement. It also has a temperature sensor to monitor ambient temperature. To save energy, when the sensor does not need sampling

data, the corresponding channel will be powered off by an analog switch.

The new accelerometer sensor boards were calibrated on a standard shaking table in Beijing Institute of Measuring and Testing. Vibration table can produce simple harmonic motions. Variety situations with different amplitudes and frequencies are used. DTFT (discrete-time Fourier transform) is used to transform the data from time-domain into frequency-domain. The results show that the accelerometer can measure in high precision.

B. Analytical Model

Because a stay-cable vibration in the vertical plane or out of the vertical plane does not couple, it can be considered as a plane problem. Stay-cable free vibration differential equation is as follow.

$$m \frac{\partial^2 v(x,t)}{\partial t^2} + EI \frac{\partial^4 v(x,t)}{\partial x^4} - h(t) \frac{\partial^2}{\partial x^2} - T \frac{\partial^2 v(x,t)}{\partial x^2} = 0 \quad (1)$$

Where: m--mass per unit length; EI--flexural stiffness of the cable; T--tension force in the cable; x--coordinate in x direction; y--coordinate in y direction; t--time; h(t)--derivative cable tension force caused by vibration.

For a cable in a cable-stayed bridge, besides its length, mass per unit length, etc. about its basic parameters, parameters such as flexural stiffness, cable sag, and cable end boundary conditions etc. will also affect its dynamic response and should be considered as well. However, with the cable length increasing, it has been found that influence on cable dynamic response from the later factors will decrease [14], [15]. When the influences, such as its sag, flexural stiffness of a stay-cable are neglected, especially for a middle length or a long length cable with length to diameter ratio greater than 50, its behaviour can be accurately modelled as a tightening string model and the solution for its governing differential equation (Eq.1) can be solved as Eq.2.

$$T = 4ml^2 \left(\frac{f_n}{n} \right)^2 \quad (2)$$

Where: l--cable calculation length; f_n --the n th natural frequency of the cable.

From Eq.2 the following two formulas about characteristics of the natural frequencies of a tension cable can be derived.

$$f_{n+1} - f_n = f_1 \quad (3)$$

$$f_n / f_1 = n \quad (4)$$

From Eq.3 and Eq.4, it can be seen that each intermediate frequency of a tension cable is distributed at the same interval and the interval value is equal to its fundamental (1st order) natural frequency. The n th order natural frequency of a cable is n times of its 1st order natural frequency.

Based on these special characteristics, a new method named Integrated Frequency Difference Method (IFDM) has been proposed to determine the fundamental natural frequency of a tension cable and this new method has been used to predict the fundamental natural frequency of a tension cable.

IV. LABORATORY EXPERIMENTS

In order to verify the feasibility and reliability of the proposed system, a cable model was built in the structural engineering laboratory of Department of Civil Engineering, Tsinghua University and the proposed system was used to measure the vibration of the cable model and its tension force was computed using the proposed IFDM method and compared with the nominal value.

A. Construction of the cable model

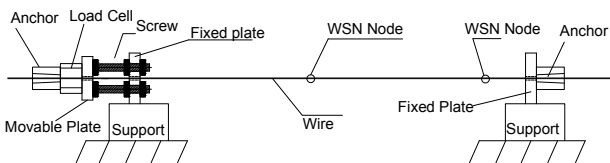


Figure 1. The cable model and WSN node

The experimental system is shown in Fig. 1. A wire was fixed to a fixed support at each end respectively, using a special anchor and a fixed steel plate (Fig.2), simulating the work condition of a cable in a cable-stayed bridge. In order to adjust the tension force level in the wire, an adjustable device consisted of four screws and a movable steel plate was adopted near the left fixed support (Fig.2). When the distance between the movable steel plate and the fixed steel plate changed by rotating the nuts on each screw step by step, the tensile force in the wire changed and was monitored by a load cell between the left anchor and the movable steel plate near the left end. The real tension force was

measured and displayed on the control computer screen.

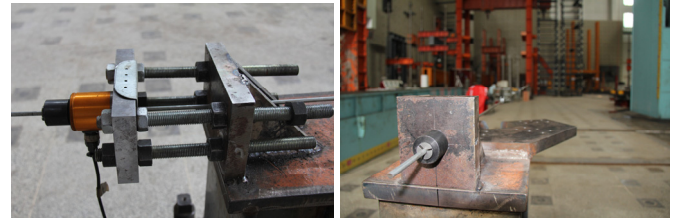


Figure 2. Site view of the two fixed ends

Two high strength wires with diameter of 5mm and 7mm respectively were used. Detailed parameters of the wires, such as diameter d , tensile strength f_{ptk} , mass per unit length m and Young's modulus E , are shown in Table 1. Measured density of the wire is 7.85g/cm^3 . The distance between the two anchors is 13.78m and 17.69m respectively.

TABLE 1. PARAMETERS OF THE WIRES

Wire	d (mm)	f_{ptk} (MPa)	m (kg/m)	E (GPa)
$\phi 5$	4.96	2033	0.15	211
$\phi 7$	6.98	1644	0.30	208

B. Establishment of the experiment system

Two wireless accelerometer nodes were fixed on the wire in the same time. One node was fixed near the middle point of the wire which can easily measure the first order natural frequency of the wire. This result was regarded as the real value and compared with the predicted value using Eq.2. However, because of site measuring condition limitation, it is difficult to fix a WSN node to the middle point of a tension cable for a real cable-staged bridge. In most cases of site measurements, the sensor node could be fixed on a cable just about several meters above the deck surface, the position of the node is just about $1/8 \sim 1/40$ of the cable length. As a result, contribution of the cable's first order vibration is very limited and high order vibration modes will be measured.

In order to simulate this condition, the second WSN node was set closely to the right fixed support to simulate the site measure condition and verify the workability and reliability of the proposed WSN system. Totally about six different fixed positions of the sensor ($L/2$, $L/8$, $L/14$, $L/20$, $L/22$, $L/28$) were considered in the cable model.

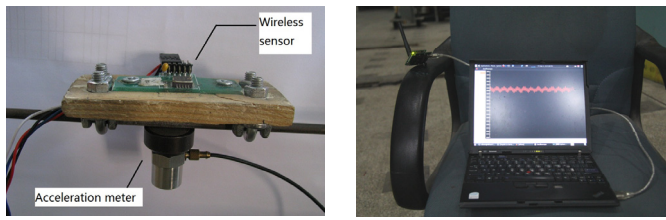


Figure 3. Site view of the sensor and data acquisition system

The wireless accelerometer node was fixed to the steel wire using a wood support and 4 bolts. For comparison, a traditional cabled accelerometer was fixed to the wire just at the same position (Fig.3(a)). By compared the results from the proposed WSN system and the traditional system, accuracy and reliability of the proposed system can be verified.

C. Data Acquisition and Analysis

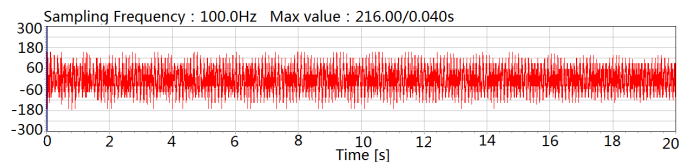
Because the mass per unit length of the wire is very small, the predicted 1st order natural frequency of the wire is far greater than that for a real cable in a cable-staged bridge. Data sampling frequency in the laboratory was set 100Hz and time range was set more than 100 second. The data was transmitted direct into a base node (another Micaz) which connected to a PC. The raw acceleration data are saved in the PC(Fig.3(b)).

TABLE 2. COMPARISON OF WIRELESS SENSOR AND TRADITIONAL METHOD

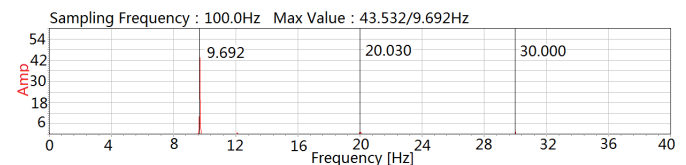
Wire type	T (kN)	L (m)	Node position	f_{theo} (Hz)	f_{test} (Hz)	Error (%)
φ5	11.77	13.78	L/2	10.15	9.91	4.53
φ5	11.77	13.78	L/14	10.15	10.01	1.36
φ5	11.77	13.78	L/20	10.15	10.16	0.10
φ5	15.65	13.78	L/14	11.71	11.59	1.62
φ5	15.65	13.78	L/20	11.71	12.11	3.41
φ5	19.92	13.78	L/14	13.21	12.99	1.67
φ5	19.92	13.78	L/20	13.21	13.09	0.95
φ7	24.06	13.78	L/2	10.28	9.89	3.81
φ7	24.06	13.78	L/14	10.28	10.06	2.15
φ7	11.77	17.69	L/2	4.18	3.99	4.38
φ7	11.77	17.69	L/10	4.18	4.03	3.51
φ7	23.92	17.69	L/2	7.98	7.69	3.63
φ7	23.92	17.69	L/10	7.98	7.69	3.61

Totally more than 20 cases were measured and analysed. Table 2 lists some results of 14 cases. Fig.4 and Fig.5 show the typical acceleration time domain curve and its power spectral density curve in frequency domain respectively for the 1st case and 3rd case in Table 2.

Two different length L , 13.78m and 17.69m respectively, were considered for φ7 wire but only 13.78m was tested for φ5 wire. Three different tension forced levels were applied to each wire and different WSN node fixed positions were considered. For each case, the predicted 1st order natural frequency f_{theo} based on Eq.2 and the measured 1st order natural frequency f_{test} based on proposed Integrated Frequency Difference Method were listed in the table.

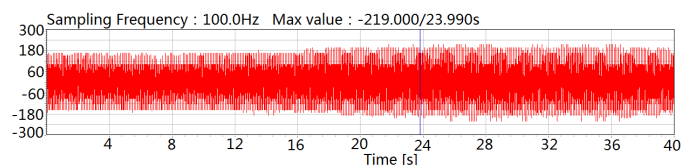


(a) Acceleration time history curve

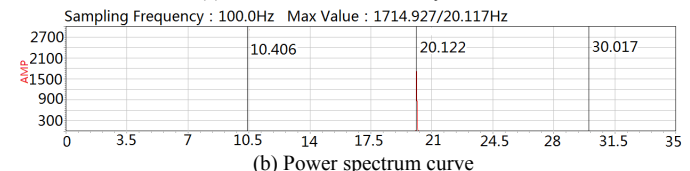


(b) Power spectrum curve

Figure 4. Time-domain and frequency domain curve for the MSN Node at middle point of the wire φ5 (Case 1 in Table 2)



(a) Acceleration time history curve



(b) Power spectrum curve

Figure 5. Time-domain and frequency domain curve for the MSN node near support point of the wire φ5 (Case 3 in Table 2)

For the first three cases in Table 2, the measured 1st order natural frequency based on traditional cabled sensor system and signal process method is 9.62Hz. The measure 1st order natural frequency f_{test} based on proposed WSN system and proposed IFDM is 9.91Hz. The theoretical value predicted based on Eq.2 is 10.15Hz. The experimental value based on proposed WSN system is greater than that from traditional method and more close theoretical value. The maximum error between the measured frequency and the theoretical value is less than 5%.

The WSN system can measure the dynamic response of a cable and accurate value of fundamental frequency. This system is feasible and reliable for cable tension force monitoring.

V. FIELD DEPLOYMENT

A. The Structure of Ronghu Bridge and its cables

Ronghu Bridge is a single fan-shaped multiple cable-stayed bridge (Fig.6). The elevation drawing of the bridge is shown in Fig.7. It has one tower which locates at about one-third of the whole bridge length. The main span is 145m long with a 5-box-shaped steel deck. The side span is 75m long with a 5-box-shaped prestressed concrete deck. The deck width is 33m and its height is 2.8m. On each side of the tower there are ten sets of stay cables (see Fig.7). From left to right in Fig7, the cables are named M10, M9, ..., M1 for the main span and B1, B2,..., B10 for the side span respectively. Each stay cables are composed of dozens of parallel high strength wires with 7mm in diameter. The wires are covered by two layers of high density polyethylene (HDPE) which the inner layer is black and the outer layer is colour.

B. Deployment of Monitoring Nodes

In order to monitor the health condition of the bridge and give warning when there are some structural damages during usage, a structural health monitoring system based on WSN has been setup on this bridge in May 2011. In this system totally 26 monitoring nodes have been deployed, including five wireless accelerometer nodes monitoring the deck vibration, two wireless accelerometer nodes monitoring cable tension force in two cables, nine wireless strain nodes monitoring steel stresses at the specified steel deck sections, nine wireless displacement nodes monitoring the settlement of the main span, an inclination node monitoring the slope of the tower.

For cable-stayed bridge, variation of the cable tension force can be used to assess the health condition of the bridge. In this system, two accelerometer nodes were fixed on cable M10 and M5 respectively (Fig.8). Both nodes are at upstream direction, main span. The nodes were located at about 4m above the deck surface, which is about 1/14th of the cable length.



Figure 6. The Ronghu Bridge in Wuxi

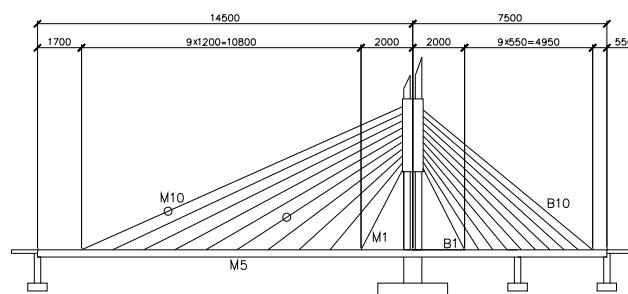


Figure 7. Elevation drawing of the Ronghu bridge (unit:mm)

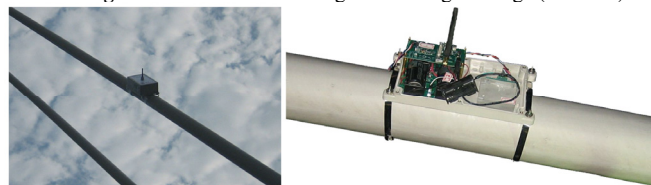


Figure 8. Sensor node deployed on the cable

C. Data Acquisition and Analysis

Data acquisition frequency was set 4 times a day. All data are transmitted through the wireless network to a server and get processed. This system has been run for several months.

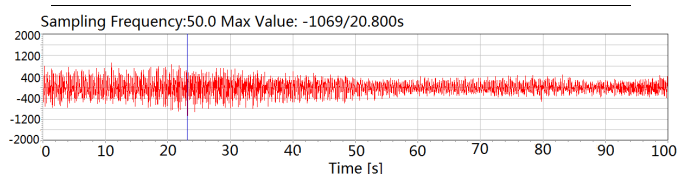
Due to the limited space, only the measured results of cable M10 and M5 based on the proposed WSN node are listed in this paper. The parameters of the cables are shown in Table 3. The WSN system works with 50Hz sampling frequency and the frequency resolution is 0.0122Hz.

Take Cable M10 as an example, Fig.10 shows its time-domain curve and its frequency domain power spectrum curve respectively. From the frequency domain curve, it can be seen clearly that due to site condition limitation, the WSN node was fixed closely to the bottom anchor and about 14th of the cable length, its dynamic response at the 4th order frequency was far stronger than that at its previous three order frequencies respectively. Based on the proposed IFDM, the 1st order frequency and then

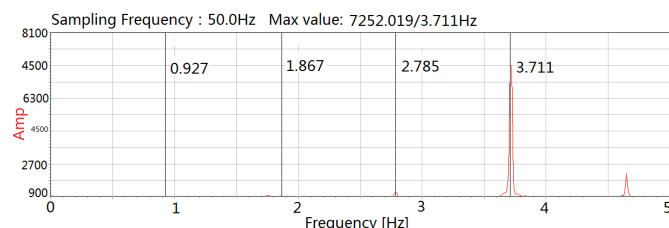
the tension force of the cable can be calculated (Table 4).

TABLE 3. PARAMETERS OF THE CABLES

Cable	Area (cm ²)	<i>l</i> (m)	<i>m</i> (kg/m)
M5	62.73	81.14	53.87
M10	71.97	140.07	61.32



(a) Acceleration time history curve



(b) Power spectrum curve

Figure 10. Time-domain and frequency domain curve for cable M10

TABLE 4. CABLE TENSION FORCES BASED ON WIRELESS SENSOR AND THE ACTUAL VALUES OF THE CABLE

Cable	<i>M</i> (kg/m)	<i>L</i> (m)	<i>f</i> _{test} (Hz)	<i>T</i> _{design} (kN)	<i>T</i> _{test} (kN)	Error (%)
M5	53.87	81.14	1.716	4143	4175	0.77
M10	61.32	140.07	0.920	4143	4070	1.77

In summary, the cable tension force predicted using the proposed system and IFDM method based on the tightening string theory is accurate for the cable tension monitoring system in Ronghu Bridge. The measured cable tension force difference is less 5%. The difference between predicted value and field measured value is quite small.

VI. CONCLUSIONS

This paper introduced a wireless sensor network based system for cable tension force monitoring. It demonstrates the feasibility and reliability of using the proposed system for a long term monitoring of a real cable-staged bridge. The proposed system has been firstly experimented on a cable model to verify its feasibility and reliability. Test results prove that the proposed system can satisfy the design requirement. It can monitor the dynamic response of a tension cable. Then the monitoring system was deployed on Ronghu Bridge, a cable-stayed bridge in Wuxi, Jiangsu Province, China. According to experimental results and field measurements, the

difference between the measured cable tension forces and the design values is less than 5%.

REFERENCES

- [1] Daihua Wang, Jianshen Liu and Degao Zhou, "Using PVDF piezoelectric film sensors for in situ measurement of stayed-cable tension of cable-stayed bridges," in *Smart Materials and Structures* 1999, vol.8. Issue. 5, p. 554-9.
- [2] Lin Yuanpei. Cable-stayed bridge [M]. Beijing: People's Transportation Press, 1994.
- [3] An Yin, Bingwen Wang and Zhuo Liu, "Design and Implementation of the Structure Health Monitoring System for Bridge Based on Wireless Sensor Network," in *Advances in Neural Networks - ISNN 2009. Proceedings 6th International Symposium on Neural Networks*, 2009, p.915-22.
- [4] Kim S., Pakzad, S., Culler, D., Demmel, D., Fennes, G., Glaser, S., and Turon, M., "Health Monitoring of Civil Infrastructures using Wireless Sensor Networks", *Proc. 6th Int. Conf. Information Processing in Sensor Networks*, 254-263 (2007).
- [5] Lynch, J. P., Wang, Y., Loh, K. J., Yi, J. H., and Yun, C. B., "Performance Monitoring of the Geumgang Bridge using a Dense Network of High-resolution Wireless Sensors", *Smart Mat. Struct.* 15, 1561-1575 (2006).
- [6] Soojin Cho, Jerome Peter Lynch and Chung-Bang Yun, "Development of a Low-Cost Automated Tension Estimation System for Cable-Stayed Bridges," in *Proceedings of ASME Conference on Smart Materials, Adaptive Structures and Intelligent Systems*, 2008, p.279-287.
- [7] Soojin Cho, Jerome Peter Lynch, Jong-Jae Lee and Chung-Bang Yun, "Development of an Automated Wireless Tension Force Estimation System for Cable-stayed Bridges," in *Journal of Intelligent Material Systems and Structures*, Oct 2009.
- [8] G. Feltrin, J. Meyer, R. Bischoff and M. Motavalli, "Modular Wireless Sensor Network for Long-Term Structural Health Monitoring" in 4th International Conference on Structural Health Monitoring of Intelligent Infrastructure (SHMII-4), 2009 22-24 July 2009, Zurich, Switzerland.
- [9] Glauco Feltrin, Olga Saukh, Reinhard Bischoff, Jonas Meyer, and Masoud Motavalli, "Structural monitoring with wireless sensor networks: Experiences from field deployments" in *First Middle East Conference on Smart Monitoring, Assessment and Rehabilitation of Civil Structures* 8-10 February 2011, Dubai, UAE.
- [10] Soojin Cho, Shin Ae Jang, Hongki Jo, Kirill Mechitov, Jennifer A. Rice, Hyung-Jo Jung, Chung-Bang Yun, Billie F. Spencer Jr., Tomonori Nagayama, and Juwon Seo, "Structural health monitoring system of a cable-stayed bridge using a dense array of scalable smart sensor network," in *Proceedings of SPIE* 2010.
- [11] Hongki Jo, Sung-Han Sim, Kirill A. Mechitov, Robin Kim, Jian Li, Parya Moinzadeh, B.F. Spencer, Jr., Jong Woong Park, Soojin Cho, Hyung-Jo Jung, and Chung-Bang Yun, "Hybrid Wireless Smart Sensor Network for Full-scale Structural Health Monitoring of a Cable-stayed Bridge," in *Proceedings of SPIE* 2011.
- [12] Qi Fu, Yan Deng and Leshan Mao, "Wireless measurement system of cable tension force based on LabVIEW," in *SICE 2004 Annual Conference (IEEE Cat. No. 04TH8773)* 2004, vol. 2, p.1067-70.
- [13] "SD122 data sheet," Low Noise Analog Accelerometer, Silicon Designs, America.
- [14] Hiroshi Zui, Tohru Shinke, Practical formulas for estimation of cable tension by vibration method, *Journal of Structural Engineering*, 1996, June:651-656.
- [15] Jiangbo Sun, Zuozhou Zhao and Honghua Zhao, "Measuring Methods of Cable Tension in Cable-Stayed Bridges" in *Advanced Material Research*, 2011, Vol.295-297, p.1230-1235.