Monitor System of Cable Tension with Fiber Bragg Grating

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ABSTRACT

Measuring cable-stayed bridge's cable tension in real time is very worthiness in construction control, cable replacing and bridge's health monitoring. A novel distributed cable tension fiber Bragg grating vibrate measuring system is designed in this paper. Utilizing the relationship between tension and frequency to measure the cable tension indirectly based on theory of string vibration. Double fiber Bragg grating micro accelerometer is designed to improve measuring sensitivity and resolution. Using continues wave tunable frequency technique to demodulate the distributed grating vibrating measuring system and applying the system in tensional stress control when build the bridge. The experiment results and theory indicate that the monitoring system has a simple structure with good stability, linear response capacity, and wide measurable range of the cable tension. It is can satisfy the needs for long term monitoring of cable-stayed bridge, as well as provide continuous and accurate information.

Keywords: cable-stayed bridges; cable tension monitoring; fiber Bragg grating; accelerometer

1. INTRODUCTION

Stayed cable is an important forced part of cable-stayed bridge, and the vast majority of the weight of cable-stayed bridge span bridge structure and the load of the bridge can be transmitted through it to the tower, real-time monitoring of cable forces for the cable-stayed bridge construction control can not only provide reliable data, but also the main basis for the bridge structural health monitoring, fault identification, determination of the operational status, accidents can be avoided by the timely processing[1]. Cable force is calculated indirectly by frequency method commonly in engineering which uses theory of string vibration and the relationship between cable force and vibration frequency [2]. As the traditional piezoelectric acceleration sensor is not suitable for long-term work in bad weather conditions, can not meet the demand for long-term Cable force monitoring [3]. Fiber Bragg Grating sensor can overcome deficiencies in the electrical devices and provides a good technical means for monitoring of bridge structures with its advantages such as high precision of monitoring, good reproducibility and long-term stability, distributed measurement as well[4-5] . In this paper, cable-stayed bridge as the project background developed the fiber Bragg grating accelerometer probe for cable force measurement and designed the distributed fiber grating cable force monitoring system which based on continuous-wave modulation, and achieved real-time monitoring of a cable-stayed bridge cable force distributed. The results of on-site monitoring show that the fiber Bragg grating sensor is an effective structure monitoring sensitive component with stable performances which can be long-term effective monitoring of cable-stayed bridge cable force and provide the basis for adjustment of cable force and replacement of cables.

2. CABLE TENSION MEASUREMENT PRINCIPLE AND SYSTEM STRUCTURE

2.1 Cable tension measurement principle

Cable tension measurement principle

According to string vibration theory, the tension of stay cable, and to consider the flexural rigidity, the dynamic equilibrium equation of cable is:

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$$\frac{w}{g}\frac{\partial y^2}{\partial t^2}+EI\frac{\partial^4 y}{\partial x^4}-T\frac{\partial y^2}{\partial x^2}=0 \qquad (1)$$

Where, y is used as abscissa (perpendicular to the direction of cable length); x is used as ordinate (the direction along the cable length); *w* is the quality of cable length; g is the acceleration due to gravity; *T* is the cable tension; *t* is time; *EI* is the flexural rigidity of the cable.

If the cable is hinged at both ends, and do not consider the cable stiffness, cable force is as follows:

$$T=\frac{4wl^2}{n^2 g}f_n^2 \qquad (2)$$

Where, l is the length of cable; n is cable vibration order; f_n is the cable vibration frequency of the nth order.

For a determined cable, w , l , g are known, if f_n can be measured accurately, and the corresponding value of n is determined, so cable tension T can be obtained.

2.2 The system structure

The distributed cable tension monitor system is shown in Fig.1. The tunable wave (1530nm~1570nm) from tunable light source is modulated by intensity and launched into $A_{ij}(n\times n)$ acceleration measuring probe by way of coupler. The vibratory signals are converted into change of wavelength and reflected back by probe with dual FBGs. The reflected signals are guided back to an optical wavelet filter and then to fiber amplifier, photo-detector, mixer, low frequency filter and computer and complete optical wavelength code and signal processing.

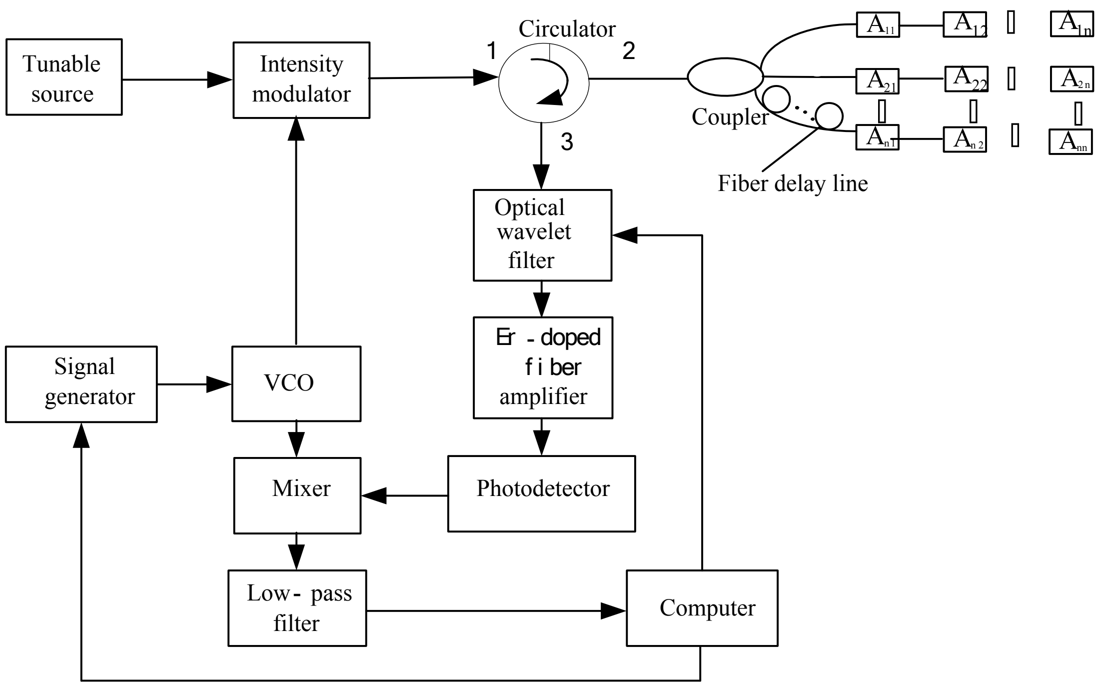

Fig.1. Distributed cable tension monitoring system

3. DESIGN OF ACCELERATION MEASURING PROBE

FBG acceleration measuring probe is shown in Fig.2. The probe given in Fig.2 is composed of a mass block (M), four spring leaves (B) and two inner-FBG waveguide bridges (C). Four spring leaves support mass block as a constraint of its vibratory direction. The Waveguide Bridge is made of silicon material which is low refractive index, stretchable and compressible. Mass block receive vibration and then apply stress on Waveguide Bridge, which result in uniform stretching strain and compressive strain on FBG in Waveguide Bridge as sensing element. Waveguide Bridge and fiber are fixed on mass block and shell frame.

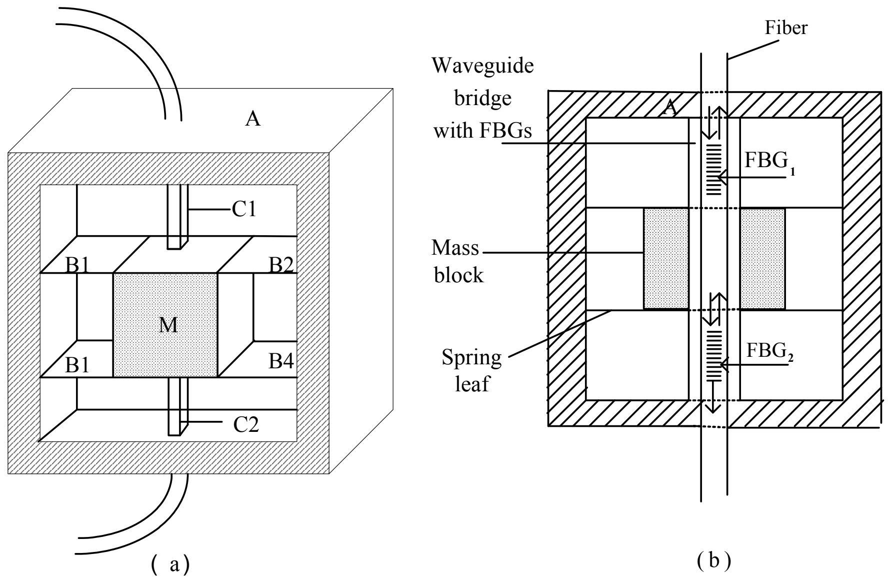

Fig.2. Acceleration measuring probe

(a) schematic diagram of sensing probe (b) sectional drawing of sensing probe.

A-frame; B1-B4- spring leaf; C-waveguide bridge; M-mass block.

The axial elastic coefficient of the two Waveguide Bridge is

$$K_w = \frac{Ebh}{l} \tag{3}$$

Where E is equivalent elastic modulus of cladding and core of waveguide material; b is width of Waveguide Bridge; h is thickness of Waveguide Bridge; l is length of Waveguide Bridge.

The elastic coefficient of the four spring leaves is

$$K_p = \hat{E} b' (\frac{h'}{l'})^3 \tag{4}$$

Where, $\hat{E}$ is elastic modulus of spring leaf; b' is width of spring leaf; h' is thickness of spring leaf; l' is length of spring leaf. The resonant frequency of mass-spring system of measuring probe is expressed as:

$$f_0 = \frac{1}{2\pi}\sqrt{\frac{2K_w + 4K_p}{m}} \tag{5}$$

The resonant frequencies of spring leaf and Waveguide Bridge are expressed respectively as:

$$f_{0P} = K_p \sqrt{\frac{\hat{E}}{\rho}} \frac{h'}{l'} \tag{6}$$

$$f_{0w} = f_{0p}\sqrt{1 + K_w \frac{Nl^2}{Ebh^3}} \tag{7}$$

When waveguide bridge generate a uniform dynamic stress, the stress on FBG is associated with acceleration, expressed as

$$\varepsilon_Z = a\frac{m}{(2K_w + 4K_p)l_w} \tag{8}$$

Where ε_Z is axial stress of FBG; a is vibration acceleration; m is quality of mass block; l_w is length of FBG.

When vibration apply on mass block which apply to waveguide bridge, grid pitch of fiber gratings on waveguide bridge change under uniform stress and result in change of reflected wavelength of fiber gratings . FBG_1 and FBG_2 are two fiber Bragg gratings which have same center reflected wavelength which are both λ_{b1} when no vibration signals whose reflectance spectrum as Fig.3 the dotted line shows.

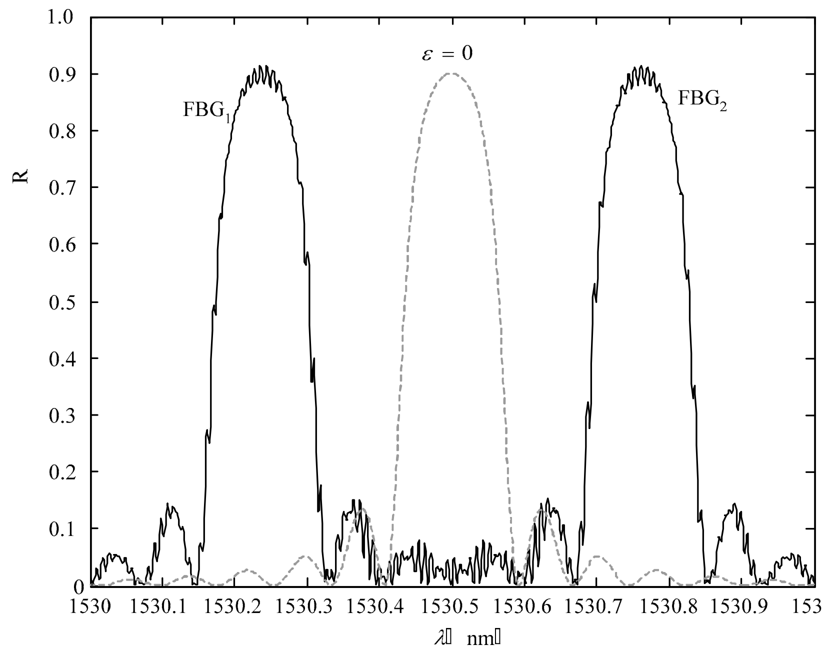

Fig.3. Measuring Spectrum of Accelerometer Probe

Suppose that compressive stress is generated on FBG_1 and tensile stress on FBG_2, wavelengths change of $FBG_1$and FBG_2 are expressed respectively as

$$\Delta\lambda_1 = \lambda_{b11} - \lambda_{b1} = \lambda_{b1}\{1 - \frac{n_{neff}^2}{2}[(1-\mu)P_{12} - \mu P_{11}]\}(-\varepsilon_Z) + \lambda_{b1}\alpha\Delta T \tag{9}$$

$$\Delta\lambda_2 = \lambda'_{b11} - \lambda_{b1} = \lambda_{b1}\{1 - \frac{n_{neff}^2}{2}[(1-\mu)P_{12} - \mu P_{11}]\}\varepsilon_Z + \lambda_{b1}\alpha\Delta T \tag{10}$$

where μ is lateral Poisson ratio; P_{11}, P_{12} are the Pockel's coefficients of the stress-optic tensor; ε_Z is axial stress(i.e., it's "+" when compressive stress is applied and per contra "-"); α is the coefficient of thermal expansion; ΔT is the temperature difference. Suppose the reflected wavelength difference of FBG_1 and FBG_2 is $\Delta\lambda$, it can be expressed as

$$\Delta\lambda = \Delta\lambda_2 - \Delta\lambda_1 = \lambda_{b1}\{1 - \frac{n_{neff}^2}{2}[(1-\mu)P_{12} - \mu P_{11}]\}\varepsilon_Z \tag{11}$$

Given $K = 1 - \frac{n_{eff}^2}{2}[(1-\mu)P_{12} - \mu P_{11}]$,then

$$\Delta\lambda = 2K\lambda_{b1}\varepsilon_z \tag{12}$$

Expression (12) indicates that the reflected wavelength difference of FBG_1 and FBG_2 $\Delta\lambda$ is independent of temperature. In the light of expression (8) and (6), we can establish the relationship of wavelength difference $\Delta\lambda$ and vibration acceleration a .

FBG is sensitive to temperature (e.g., the temperature sensitivity of fiber grating whose center reflected wavelength is near of 1550nm is 0.01nm/℃), so temperature compensation must be taken into consideration in acceleration measurement system based on FBG sensing element. In the scheme we proposed, sensing signal is the wavelength difference, so the influence of temperature change factor on measurement result is avoided during measuring and furthermore the sensitivity and resolution are enhanced double.

4. SYSTEM OF MEASUREMENT AND SIGNAL PROCESS

In the system shown in Fig.1, with FMCW technique and comb filter technique, the 40nm-width light from the tunable source is modulated to sawtooth wave whose frequency is proportional to its time by intensity modulator and launched into the measuring probes via coupler. The distribution of probes can be expressed as

$$\begin{bmatrix} A_{11} & A_{12} & \cdots & \cdots & A_{1n} \\ A_{21} & A_{22} & \cdots & \cdots & A_{2n} \\ \vdots & \vdots & \ddots & & \vdots \\ \vdots & \vdots & & \ddots & \vdots \\ A_{n1} & A_{n2} & \cdots & \cdots & A_{nn} \end{bmatrix} \tag{13}$$

Each probe has two FBGs, so center reflected wavelength in measuring can be expressed by wavelength matrix as follows

$$\begin{bmatrix} \lambda_{b11}\lambda'_{b11} & \lambda_{b12}\lambda'_{b12} & \cdots & \cdots & \lambda_{1n}\lambda'_{1n} \\ \lambda_{b21}\lambda'_{b21} & \lambda_{b22}\lambda'_{b22} & \cdots & \cdots & \lambda_{b2n}\lambda'_{b2n} \\ \vdots & \vdots & \ddots & & \vdots \\ \vdots & \vdots & & \ddots & \vdots \\ \lambda_{bn1}\lambda'_{bn1} & \lambda_{bn2}\lambda'_{bn2} & \cdots & \cdots & \lambda_{bnn}\lambda'_{bnn} \end{bmatrix} \tag{14}$$

where λ_{bij} and λ'_{bij} are respectively the center reflected wavelengths of the two FBGs of *i*th low and *j*th line in matrix. It's proved theoretically and experimentally that the resolution of FBG can reach to $0.6\times 10^{-9}\ nm/\sqrt{Hz}$ above 100Hz and to $7.5\times 10^{-7} nm/\sqrt{Hz}$ between quasi-static state to 1000Hz and the tunable range of light source can reach to 40nm(1530nm~1570nm) easily. For measurement of acoustic wave vibration acceleration, it's proved experimentally that wavelength change of FBG is only 1.2nm when acceleration is 340m/s^2. So in the practical system, it's enough that the bandwidth of FBGs in each probe is given 4nm, thus, the quantity of point measured distributed can reach to 36, that is n=6.

The light signal is modulated with a sawtooth wave by computer controlling a voltage-controlled oscillator (VCO) and the center reflected wavelengths of FBGs in $n \times n$ measuring probes are different, so modulated light is guided to each probe non-synchronously, that is, the sawtooth wave frequency when modulated light reach to each probe is different. The reflected signals from FBGs are guided back to a tunable optical filter and each wavelength change $\Delta\lambda_{ij}$ which denote vibration acceleration signal is attained. The signals are transferred into electrical signals by photo-detector and mixed with a reference sawtooth signal, as shown in Fig.4. Because of the micro interval between the two FBGs in each probe, intensity modulating frequency is considered equivalent. Make Δf_{ij} (difference frequency signal of each sensing signal and reference signal) correspond with $\Delta\lambda_{ij}$ (the center wavelength difference of the two FBGs in one probe) by optical code and then acquire $\Delta\lambda_{11}, \Delta\lambda_{12}, \cdots, \Delta\lambda_{1n}; \Delta\lambda_{21}, \Delta\lambda_{22} \cdots, \Delta\lambda_{2n};\ \Delta\lambda_{n1}, \Delta\lambda_{n2}, \cdots,\ \Delta\lambda_{nn}$, and further fulfill measurement of acceleration $a_{11}, a_{12}, \cdots, a_{1n};\ a_{21}, a_{22}, \cdots, a_{2n}; \cdots, a_{n1},\ a_{n2}, \cdots, a_{nn}$.

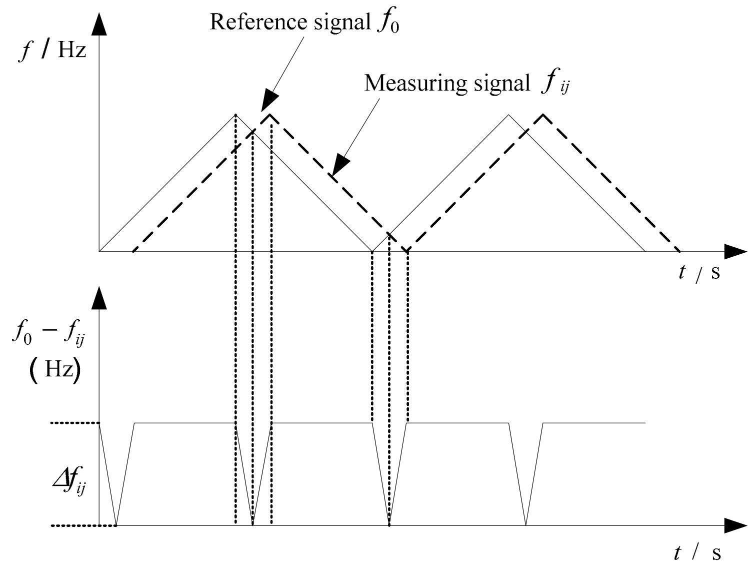

Fig.4. Schematic diagram of difference frequency signal generation

5. MATHEMATICAL EQUATIONS

The monitored cable-stayed bridge is the folding tower double cable plane cable-stayed bridge, as total length of 567.11m, of which the bridge is 378.1m; the approach road is 189.01 m. The main bridge is single-tower asymmetric cable-stayed bridge with double cable plane, span is 40 m + 108 m + 16 m + 26 m. Structural system is a consolidation system with the pier, tower, beam, the cable tower was broken line which up straight and down ramps, the horizontal model of cable tower is the inverted Y-shaped, and the main span cable using fan-shaped arrangement, horizontal using A-shaped arrangement of double-cable-plane. The height above the bridge deck of cable tower is 50m, height of tower piers is 7.3m, and under the cable tower facade is 30m high above. Main span girder is the double-triangle box ribbed section, composed of two triangular beams, bridge beams and panel, the structure is shown in Figure 5.

Characteristic parameters of cable-stayed model are shown in table 1, as the top cable fixed, cable tension can be adjusted through the lower end of the cable and measured in different circumstances with the use of fiber Bragg grating measuring system.

Acceleration sensor probe of cable force monitoring system is installed between the cable anchor and plate hole in the cable-stayed bridge, with the both ends to bear the cable force. In the effects of train-bridge coupling and wind-induced vibration, the cable is always in a state of vibration. Arranging a number of vertical measuring points in the stay cable, while using the grating acceleration sensor to obtain the acceleration response, the natural frequencies value of cable was obtained by the data acquisition processor for data acquisition and processing of its output. With the relationship between cable tension and its inherent frequency to achieve cable tension indirectly according to string vibration theory.

The layout of the self-vibration characteristic measuring point and the cross-sectional measuring point is shown in Figure 6, According to self-vibration testing, the self-vibration parameters are shown in Table 2. In different circumstances of tension, comparing cable force measured value with the design value with fiber Bragg grating sensor, the result is shown in Figure 7.

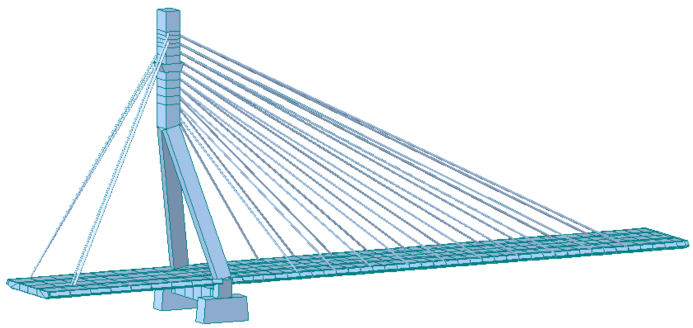

Fig. 5. Structure of the cable-stayed bridge

Table. 1. Character parameter of cable-stayed bridge module

Parameter Name	Parameters of the size
Cable length	2.8m
Cable inclination	30°
Cable diameter	0.003m
Cable stiffness	5.0×10^5N
The quality of cable per unit length	0.26kg/m

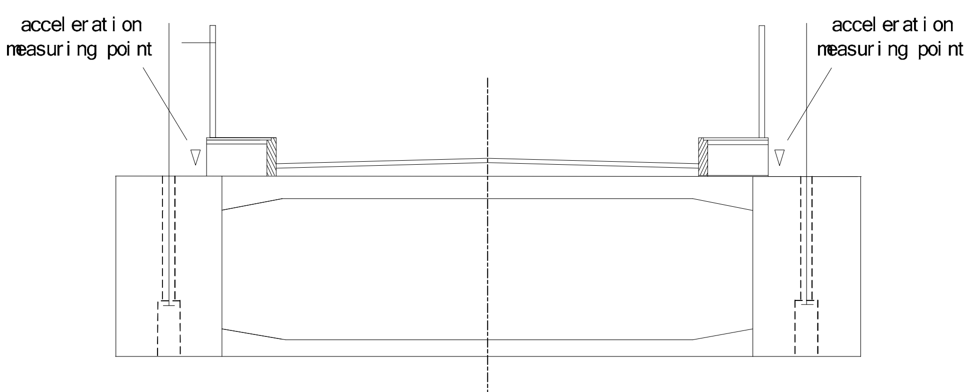

Fig. 6. FBG accelerometer testing point arrangement

Seen from the experimental results, cable tension measured by fiber Bragg grating accelerometer sensor is close to the designed data which shows that this method is effective and feasible. The system has a lot of good characteristics such as simple structure, wide measurement range, stability and linearity. Combination with the computer monitor, predicting the trends of cable force according to a large number of test data, providing the basis for the cable force adjustments and the replacement of cables, and achieving the monitoring and alarm of cable force in an anomalous situation, is of great significance to the safety of entire cable-stayed bridge.

Table. 2. Character parameter of self oscillation

order	Frequency (Hz)	damping ratio
1	0.528	0.0148
2	0.772	0.0192
3	1.286	0.0167
4	1.389	0.0295
5	1.697	0.0287

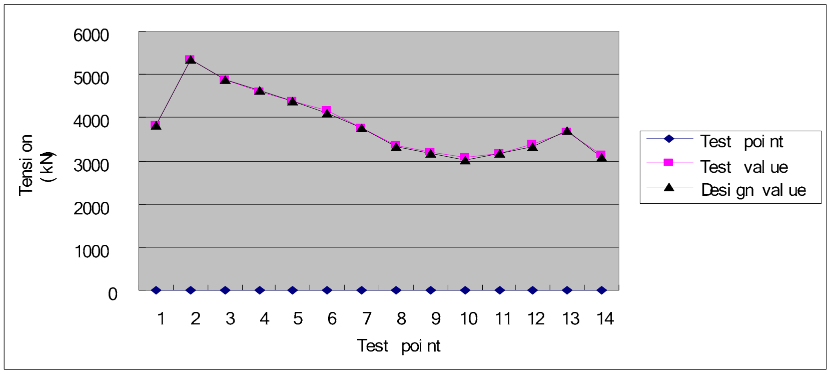

Fig.7. Value of measuring cable tensions

6. CONCLUSIONS

Using fiber Bragg grating sensor array to achieve real-time online monitoring of cable-stayed bridge cable force, overcome the disadvantage that the traditional piezoelectric sensors can not meet the needs of long-term field monitoring. The monitoring system is designed with simple structure, wide measurement range, stability, and good linearity and so on, which applies not only to the cable force measurement in the tensioned process of construction, but also applies to the security monitoring of cable-stayed bridge cable force after the construction, providing the basis for the cable force adjustments and the replacement of cables. Long-term monitoring of cable force change data can grasp the run situation of the bridge in time, make sure of the conservation and maintenance to the bridge in time, and avoid the occurrence of major accidents, of great significance.

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