Application of Fiber Bragg Grating Sensor in A National Scientific Device

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Abstract: Using fiber bragg grating(FBG) sensor to monitor the strain of connecting bar, which connects the Acrylic sphere and steel structure in central detector of a national scientific device. The stability and static parameters of FBG sensor had been tested before calibration. Experimental results show that Linearity Coefficient is above 0.9999, Linear Error is less than 0.75%, Repeatability and Hysteresis Errors are less than 0.50%, the maximum Synthetic Error is 0.90%. And the stability and durability can meet the engineering demand of strain monitoring for the central detector. The monitoring system can meet the long-term health monitoring requirements. The experiment testing accumulates construction experience for connecting bar stress detection.

1. Introduction

A national scientific device is designed to determine neutrino, which including a tunnel, an underground experiment hall, a water pool, a central detector, a muon tracking detector, and some ancillary facilities at 700-meter deep underground. The central detector is filled with 20 kilo-ton liquid scintillator. Liquid scintillator is sealed in Acrylic sphere which is surrounded by 18,000 20'' photomultiplier tubes (PMTs) and soaked in a huge water pool. The Acrylic sphere is supported by steel structure through connecting bar [1]. The inner diameter of Acrylic sphere and steel structure is 35.4 meter and 40.1 meter. There are two types connecting bars, their diameters are 82mm and 60mm. The strain monitoring system of connecting bar is a part of central detector. The requirement of strain measurement error is not more than 5%.

2. Strain Monitoring Installation Scheme Design

The maximum push and pulling force in Z axis of connecting bar is 15 ton and 9 ton by simulation. So the strain of bar is micro-strain. There isn’t external shock except of earthquake occurs in operation. The monitoring system must working normally for over 20 years as central detector will be in a closed state after construction project closeout, only a chimney on the top. It is impossible for routine maintenance even if the sensor and measuring circuit are out of order. The central detector is surrounded by PMTs to capture weak signals of neutrino, and there are other kinds of test equipment also, so signal anti-interference is important for strain monitoring system.

Considering the monitoring system working under water, more than 590 measuring points, and measuring distance is long, so the FBG sensor is used to monitor the strain of connecting bar. As FBG
sensor has the advantages of good tightness, lightweight, small size, long transmission distance, easy-formed networks, high sensitivity and anti-electromagnetic interference capability.

FBG sensor is usually attached to elastomer and sealed for protection. When the force is applied to the elastomer, strain occurs along the elastomer with FBG, which lead to the peak of reflected wavelength shift. The temperature, stress or strain is sensed by measuring the wavelength drift [2].

There are different types of sensors, and there are different ways of installation. But these sensors have something in common is that the stress and strain must be effectively transferred from the measured volume to the elastomer. As shown in Fig. 1, in the process of measurement, the elastomer converts the measurands such as force, pressure, displacement, torque, acceleration into strain or stress, and then the strain or stress is converted into the shift of wavelength by means of FBG as sensitive element [3]. The connection between the elastomer and sensor has a great influence on the accuracy and long-term stability of the measurement.

![Figure 1 Strain Transfer Diagram of FBG Sensor](image)

In order to monitor the strain effectively, a fixture is designed to fasten FBG sensor on connecting bar. The base of fixture is welded on connecting bar, FBG sensor is fixed in base by fastening screws. The material of fixture and connecting bar is the same, so that the stress of connecting bar is effectively coupled to the sensing system. There is not looseness, buffering and other reasons to reduce system coupling, so the measuring accuracy is not affected. On the other hand, as the material of sensor support, installation fixture and connecting bar has the same thermal expansion coefficient, there is not large shear stress occurs when the temperature changing [4]. The installation scheme of strain monitoring system of connecting bar in the central detector is shown in Fig.2.

![Figure 2 Installation Scheme of FBG Sensor](image)

**3. System structure**

As shown as in Fig.3, The FBG monitoring system mainly consists of wideband optical fiber source, FBG sensors, wavelength demodulator based on tunable F-P filter, computer and the analysis and processing system.
The FBG monitoring system has several channels. Each channel can connect multiple FBG sensors in series by one optical fiber. A set of stress sensing information is obtained by demodulator, and then input to the computer for data analysis and processing. The range of wavelength is 1510~1590nm in FBG strain measurement scheme. There is no conflict with PMTs in the range of wavelength, and the optical fibers are hermetically coated also. Even in extreme cases of damage to the optical cable, the PMT test will not be affected. For each channel, considering the full scale of FBG sensor is 3nm. The range of 80nm is divided according to each FBG sensor and the definite allowance is retained, using Wavelength Division Multiplex(WDM) [5], so one fiber can connect about 18 FBG sensors in series. Normally, 10~15 sensors are connected in series to one fiber. Distributed monitoring can be realized by connecting several fibers in parallel to demodulators.

The sensors operate under closed pure water system. If one sensor is found that out of order, the other side of the fiber can be connected to the demodulator and other sensors can still work effectively to achieve disaster recovery purposes.

The central detector system is working deep under ground 700m and the temperature fluctuations are very small. So temperature compensation is not required. A type of FBG sensor with low sensitive to temperature and structure stability has been selected to monitor the strain of connecting bar.

4. Experimental Testing
Sensors need to be calibrated before engineering installation so as to establish the relationship between the push or pulling force of the connecting bar and the strain of the sensor. The stability of the monitoring system is very important in calibration. If there is no good long-term stability, zero drift will be generated. Then the source of error cannot be determined accurately, calibration will lose its meaning [6].

4.1 Stability Testing
There are many factors affect the long term stability of sensors, the main factor is the change of the strain transmitting characteristics caused by the coupling effect of heat and force [3]. The fastening between sensor and elastomer is the key factor of strain transmitting characteristics changing. The sliding or creep of the fixed end of FBG sensor will cause wrong information. Of course, laser welding is the best way, the FBG sensor element is welded deep and without thermal stress, and welding does not require filling material to avoid corrosion. But in the calibration stage, sensor must be taken off after calibration and welding will damage the sensor. So a suitable fixture to lock the sensor must be designed, make the sensor as close to the connecting bar as possible, and there must be no looseness after fixed. The fixture’s material is as consistent as possible with the connecting bar, and proper pre stretching of FBG sensor is needed when fixing [7].
4.1.1 Testing Plan
The base of the fixture is welded on testing steel column which diameter is 60mm, FBG sensor is fixed in the base by fastening screws, and ambient temperature is room temperature 25±1°C. The reflected wavelength of the FBG sensor is recorded and stored in computer per second. The testing is last 30 days by loading 30kN using Pressure Tester. 
Experimental Equipments are (a) FBG demodulator, type: JEME-iFBG-S15. There are 15 channels, the measurable wavelength range of each channel is 1510~1590nm, resolution is 1pm, stability is ±2pm. (b) Pressure Tester, type: DL-300. The range of force is 30kN-300kN, and the accuracy grade is 0.1.

4.1.2 Testing result
There is a large amount of wavelength output data stored in computer every day. The datum at 17 o’clock is taken out randomly and shown in Fig.4. It shows that the reflected wavelength fluctuations is small, the change is relatively stable. It means that using the designed fixture, the monitoring system has high stability under a certain load for a long time.

![Figure 4 Stability Curve of Sensor(25°C)](image)

4.2 Sensor Characteristics Testing
The testing connection bar is a steel column, the diameter is 60mm, the length is 500mm and material is 304 Stainless Steel. The strain can be calculated as eq.1

\[ \varepsilon = \frac{F}{SE} \]  

Where F is the stress on steel column, S is the sectional area and E is longitudinal modulus of material. For 304 stainless steel, E=193kN/mm². So the theoretical strain is 1.83 \( \mu \varepsilon /kN \).

Three fixtures are set in 120 degrees apart from each other on testing connecting bar. FBG sensors are fixed by screws. The pressure tester outputs the pressure at intervals of 30kN, from 0 to 150kN, then from 150kN to 0. Load and upload the measured pressure to testing sensors step by step and repeat the cycle three times. The wavelength of the FBG is recorded after each loading pressure been in stabilization, and the load will be kept for 10 seconds, all data will be stored automatically. Under different pressure, the wavelength shift \( \Delta \lambda \) of three FBG sensors on testing bar is shown in table 1. The unit of \( \Delta \lambda \) is pm.

| Pressure(kN) | Round 1 | Round 2 | Round 3 | Round 1 | Round 2 | Round 3 | Round 1 | Round 2 | Round 3 |
|--------------|---------|---------|---------|---------|---------|---------|---------|---------|---------|
| 0            | 773.5   | 772.8   | 771.4   | 2910.4  | 2908.6  | 2906.8  | 2910.4  | 2908.6  | 2906.8  |
| 30           | 582.8   | 581.4   | 583.0   | 2593.4  | 2592.3  | 2592.1  | 2593.4  | 2592.3  | 2592.1  |

Table 1. The Wavelength Shift of Three FBG Sensors on Testing Bar
The data will be linear fitting by least square method, and then calculating Linear Coefficient $R$, Linear error, Hysteresis error, Repeatability error and so on [8], which is shown in Table 2.

| FBG sensor | FBG 1 | FBG 2 | FBG 3 |
|------------|-------|-------|-------|
| Central Wavelength ($\mu m$) | 1521.199 | 1525.742 | 1529.164 |
| Sensitivity ($\mu m/kN$) | -6.208 | -10.939 | -8.458 |
| Linear Coefficient $R$ | 1 | 1 | 0.9999 |
| Linear Error $\delta_L$ | 0.58% | 0.60% | 0.75% |
| Hysteresis Error $\delta_H$ | 0.34% | 0.32% | 0.42% |
| Repeatability Error $\delta_R$ | 0.18% | 0.22% | 0.25% |
| Synthetic Error $\delta_T$ | 0.70% | 0.72% | 0.90% |

The Hysteresis and Repeatability curves of FBG1 from Table 1 are shown in Fig.5.

The Synthetic Error $\delta_T$ can be calculated as eq.2. Three FBG sensors on steel columns are 0.70%, 0.72%, 0.90% as shown in Table 2.

$$\delta_T = \sqrt{\delta_L^2 + \delta_H^2 + \delta_R^2}$$

(2)

The Linearity Coefficient $R$ of each FBG sensor is above 0.9999, which means that the testing system has a good linear output. The FBG 3 has the maximum Synthetic error, which is 0.90%. It may be caused by installation or sensor itself. But all of Synthetic error is less than the requirement of 5%. It is concluded that the strain of the steel column can be obtained accurately by measuring the strain of the FBG.

As shown in Table 2, the sensitivity of the three sensors is quite different. After the analysis, the main reason is that the location of these three sensors is different. For one sensor, the sensitivity is not the same when the installation position is different. Six sensors had been tested at the three positions and
the sensitivity is shown in Table 3. Their average of sensitivity of six sensors is \(-8.50 \frac{pm}{kN}\), as the theoretical strain is \(1.83 \frac{µε}{kN}\), means there is \(-4.68\)pm wavelength shift per micro-strain.

As shows in Table 3, the sensitivities of sensors are not very different from each other. It means that the sensitivity is closely related to the installation position, as the bearing area of experimental loading tool or the steel columns is out-of-flatness, or the steel columns places out of center. Consequently, the force of the steel columns is uneven, so the stress loaded on the sensors at different positions are not the same. But the average load on three sides of the bar should be the same. So the average of the measured sensitivities is the same. In the actual measurement, the sensors shall be placed in 3 different positions to test the sensitivity respectively. The positions are set in 120 degrees apart from each other. The average value is used as the stress calibration factor.

Table3. The sensitivity of the 6 sensors

| FBG Sensor | FBG 1 | FBG 2 | FBG 3 | FBG 4 | FBG 5 | FBG 6 |
|------------|-------|-------|-------|-------|-------|-------|
| Position 1 | -10.93 | -10.82 | -10.80 | -10.94 | -10.94 | -10.872 |
| -9         | 5     | 8     | 5     | 3     |       |       |
| Position 2 | -6.208 | -6.210 | -6.229 | -6.257 | -6.225 | -6.303 |
| -3         |       |       |       |       |       |       |
| Position 3 | -8.518 | -8.502 | -8.506 | -8.691 | -8.650 | -8.458 |
| -8.555     | -8.512 | -8.515 | -8.631 | -8.606 | -8.544 |       |
| Average    |       |       |       |       |       |       |

As shown in table 2, the Repeatability and Hysteresis error of sensors are less than 0.50%. It shows that the testing system has good stability. The elastic hysteresis between the sensor and the stainless steel column is small, the gap between them is reasonable and the fasteners are not loose. The method of installing FGB sensor on the base of fixture is practical.

5. Conclusion
FBG sensor is passive component with long distance transmission, corrosion resistance, anti electromagnetic interference. It has good long-term stability and durability, which is suitable for working underwater for a long time. FBG sensors will be used to monitor the stress of connecting bar in central detector of a national scientific device. Experimental results of linearity, sensitivity and stability show that FBG sensor can monitor the stress changes of the connecting bar effectively and accurately. The strain monitoring system of connecting bar can meet the requirements of long-term stress monitoring. In addition, WDM technique is used to connect multiple FBG sensors in series with one optical fiber. Distributed monitoring can be realized in central detector of a national scientific device by connecting several fibers in parallel to demodulators.

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