Review on Optical Fiber Sensing Technologies for Industrial Applications at the NEL-FOST

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ABSTRACT

The research on engineering experiment is a key step in translating technical development to industrial application. According to our practical experience for more than 30 years and some applications of the fire alarm system, bridge, coal and power safety ensuring system, this paper reviews on engineering technique problems in the application of fiber optic sensor and their solutions, which may provide some references for wider industrial applications.

Keywords: *fiber optic sensor, engineering experiment, fiber grating, optical fiber sensing network*

1. INTRODUCTION

Optical fiber sensing technology has drawn attentions worldwide and obtained a number of theoretical achievements in the last decade of rapid development. The ultimate aim in the development of optical fiber sensing technology is to display and exhibit its technical superiority, and therefore generate wide applications in industry. The research on engineering experiments should be recognized as a key step in translating technical development to industrial application, and therefore becomes one of the key technologies. Besides fundamental research on frontier science exploration, some key techniques for optical fiber sensing technology should be thoroughly investigated according to practical engineering demands, in order to solve technical problems and therefore to be used more effectively. This paper reviews on several typical technical problems and solutions in engineering application with some concrete application cases including fiber optic sensing safety monitoring system for fire, bridge, coal and power. It is expected to provide some useful hints for wider industry applications.

Due to its unique advantages including light weight, low-cost and immunity to electric-magnetic interference, optical fiber sensors have found wide applications in many fields. Nowadays lots of optic sensing components have been developed including temperature sensors, stress/strain sensors, vibration sensors, fiber optic hydrophones and gas sensors. However there still exist gaps to meet customer demand such as problems of resisting harsh environment, FBG sensing network with large capacity, demodulation devices for different demands and lack of complete set of technology and system [1-9]. Therefore application-orientated development is required to solve the problem between research investigation and industrial application.

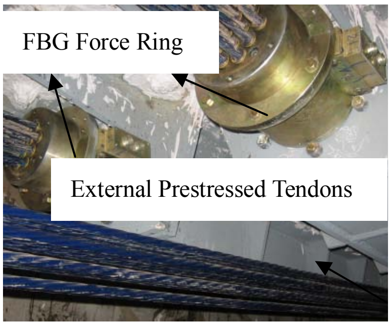
The National Engineering Laboratory for Optic Fiber Sensing Technologies at Wuhan University of Technology has conducted research and development activities on optical fiber sensing technologies for more than 30 years, this paper will review on some technological achievements they have made including monitoring technology of FBG in harsh environment such as high temperature, large strain etc, multi-point monitoring with large capacity, various forms of demodulators, complete technology and system development. Some concrete industrial applications include long-term safety monitoring of the high-speed railway, cable-stayed bridge with the largest span and load in the world, fire safety monitoring of the world's largest road tunnel, long-term leakage and structure safety monitoring of the world's highest concrete face dam, fire alarm system of four national strategic oil storages and 90% of large oil tanks in China Petrochemical Company, fire and structural safety monitoring of the first subsea tunnel in China, fire alarm system of the largest group of tunnels in China and structural safety monitoring of key cultural relic protection projects in Three Gorges.

2. OPTICAL FIBER SENSOR FOR STRUCTURE HEALTH MONITORING

Bridge strengthening and maintenance is the most important work of bridge safety. The bridge general status and the reinforcement effect can't be monitored effectively using conventional strengthening and maintenance methods. It is a necessary and urgent task to develop a new type of sensor monitoring system, for the real time and long term monitoring of loading state and reinforcing effect of the old bridges. We have constructed a real-time, multi- parameters and long-distance reinforcement monitoring system by combining the optical fiber sensing technology which has particular advantages with the mature conventional reinforcement methods.

Wuhan Second Yangtze River Bridge is a super-large bridge which spans the Yangtze River and connects Hankou and Wuchang in Wuhan city. It was constructed and opened to traffic in 1995. After the bridge was inspected in 2006, the project for its strengthing and maintenance began. The project including 4 parts: (1) the continuous prestressed concrete beam(CPCB)bridge (7×60m), which was located between the No.0 to No.7 pier in Hankou bank; (2) the continuous prestressed concrete rigid frame(CPCRF)bridge (83+130+125)m, which was located between the No.7 to No.10 pier in Hankou bank; (3) the CPCRF bridge (125+130+83)m, which was located between the No.13 to No.16 pier in Wuchang bank; (4) the CPCB bridge (65.425+126+65.425)m, which was located between the No.16 to No.19 pier in Wuchang bank. According to the bridge diseases, the reinforce actions and construction orders were: (1) grouting and closing cracks; (2) setting external prestressed tendons; (3) bonding of carbon fiber composite sheets; (4) maintenance

The external prestressed tendons are fixed on the surface of concrete structures and acts on the bridge structures through deviating structures and anchor structures of the maintenance system. As a result, the structure stress is adjusted and restored to the original load-carrying capacity and then the structure performance is improved. It has the most obvious effect for improving the stress and alignment of the bridge structure. The tension force of the external prestressed tendons should be real time monitored during the tension process. In order to monitoring the tension force, the fiber Bragg grating force rings were separately installed on the external prestressed tendons of the CPCB bridge in Hankou bank, the CPCRF bridge in Hankou bank and the CPCRF bridge in Wuchang bank with the number of 12, 12 and 8 as shown in Fig.1 during the bridge strengthening and maintenance process. All the FBG force rings were installed in the tension side and were installed exactly before the tension process.



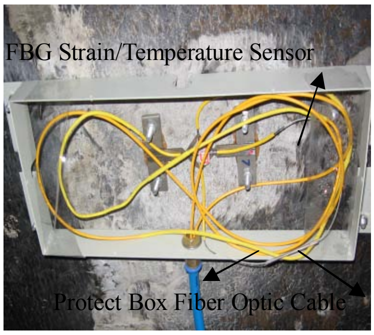


Fig.1 FBG force ring Fig.2 Differential FBG displacement cell Fig.3 FBG strain/temperature sensor

In order to monitoring the cracks change during the tension process of the external prestressed tendons, the typical cracks of the CPCB bridge and the CPCRF bridge in Hankou bank were selected and monitored with differential fiber Bragg grating displacement cells. The section near pier No.7 of the CPCB bridge was selected as the sensor installation section. A group of sensors were installed across the typical cracks of the web slabs. And the three sensors were taken as a group. In the same way, the section near the pier No.10 of the CPCRF bridge was selected. The sensors installation method was the same as above. Figure 2 shows the on-site installation of the differential FBG displacement sensors.

3. OPTICAL FIBER SENSOR FOR HIGH-SPEED RAILWAY MONITORING

To design a high-speed railway, the track line must be straight, and a switch should avoid to be put on a bridge, however, in the rugged mountain area, the station, tunnel and bridge may be connected together to form a flat line. Track switch and its ballastless concrete sleeper slabs have to be installed on a bridge. In the 350km/h high speed railway from Wuhan to Guangzhou, China, on a continuous beam bridge, Leida bridge, it is the first time that a switch and its slabs were fixed on a bridge in the world[1]. The influence of climate, geology and the dynamic impact by passing high speed trains cause high stress in the track, slab, and bridge, specially the variation of environment temperature makes the continuous beam of the bridge expansion or contraction. The designers estimated that when the environmental temperature rises 1°C, a 20kN stress generates to press the 60kg/meter track. And it causes both the track creeps on the slab and slab creeps on the bridge body. In order to keep switch track working in a safe condition, the quantitative value of both creeping displacement must be monitored. However, because the track is used as return circuit of train power, and the voltage is as high as 27.5kV, and under the open-air meteorological conditions, it is difficult to use the traditional electrical sensors. The operation principle of fiber Bragg grating (FBG) is to control the properties of light propagating in the fiber, different from the electrical sensors. FBG sensing technology is of high accuracy, good stability, moisture-proof and anti-electromagnetic interference. Specially, only could the FBG do the long term monitoring in engineering field. This has led FBG becoming a strong competitor to measure the stain, temperature and displacement in constructions.

There are two kinds of measurement range of displacement cells, 30mm and 50mm. The former is for detecting the displacement of the track, and the latter is for slab displacement detecting. A FBG displacement cell is shown in Fig.4, and Fig.5 is its inner structure. The displacement of the detected object pushes or pulls the spring tie, which is connected with an end of a spring. The other end fixes with a strain equivalence beam, and makes it bent. The trapezoidal beam is used as a sensing unit and the place for two FBGs fixing on. By means of the spring, when the tie moves its whole 30mm or 50 mm measuring range, the beam bends just 1mm. That is its measurement extending function.

Two FBGs are respectively glued on the left and right surface of the beam. When the beam is bent leftward, the right surface is tensed and its strain is positive, as a consequence, the wavelength shift responding from tensile FBG A is also positive. On the other hand, the left surface is compressed; therefore, its strain is negative. So the wavelength shift responding from compressed FBG B, is also negative. The Bragg wavelength of FBG A is 3nm longer than the FBG B.

Fig.6 shows a spectrogram of Bragg wavelength of a 50mm displacement loaded. The left group of curve in Fig 8 is from the compressed FBG, and the right group is from the tensile FBG. When the spring tie is at zero position, their peaks are at each 0mm respectively. When it is drawn out half range, 25mm, their peaks at their each 25mm. Peaks are at each 50mm, when the tie is drawn out to full 50mm. Fig.6 also illustrates how shift superimposition and temperature compensation work. To add two absolute values of wavelength shift from 0mm to 50mm, the summation of shifts by tensile and compressed FBGs doubles the wavelength response. Because the wavelength shift is not only caused by the load, but temperature change can do the same. The way of putting two FBGs in opposite shift direction eliminates the shift caused by environment temperature change[3].

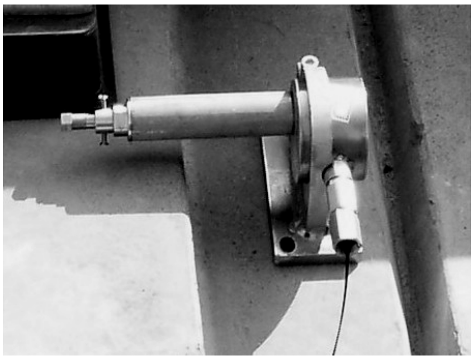


Fig. 4 A FBG displacement cell

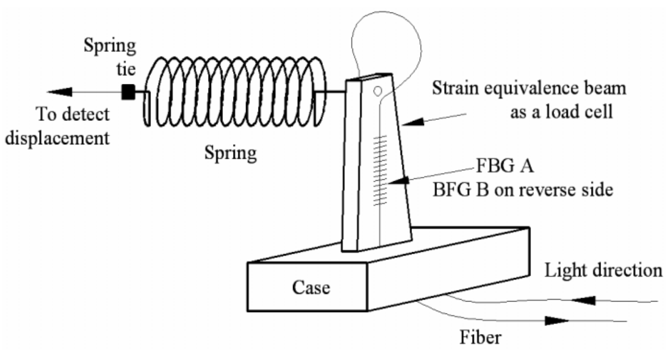


Fig. 5 Structure schema of displacement cell

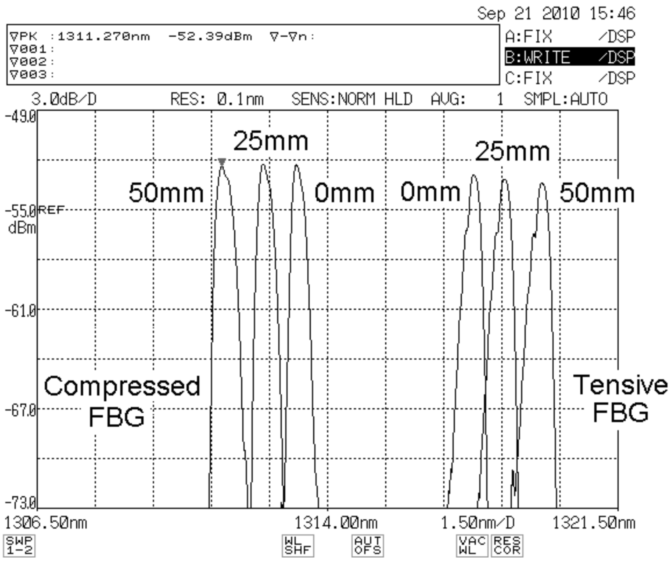


Fig.6: Spectrum shift under load

54 FBG displacement cells are symmetrically installed along the central line of whole 196-meter long switch section on the Leida bridge. 32 of them are used to monitor the displacement of track on the slabs, and the rest 22 monitor the displacement of the slabs on the bridge. All wavelength signals are transmitted to a 32-path demodulator by multi-fiber optical cables and transmitted by the WDM method. They are illustrated as Fig.7.

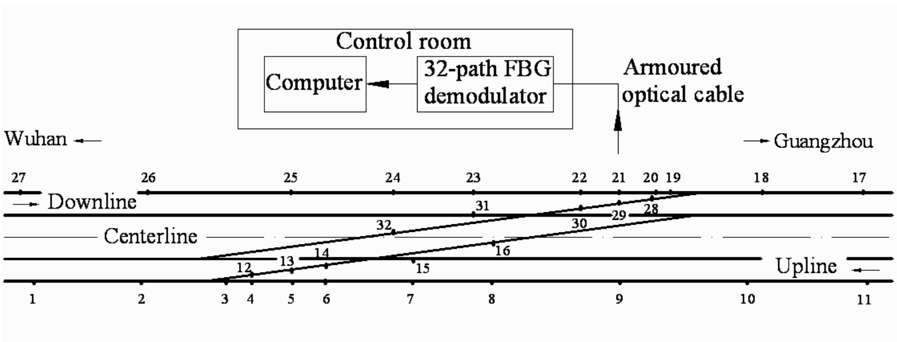


Fig.7 Schema of distribution of 32 track displacement cells

Fig. 8 shows the installation of these two kinds of displacement cells. Fig. 9 and Fig. 10 give the detail installation of each kind cell. Reliability is a key demand for a device used in the site of high speed railway. Reliable packaging and protective methods are adopted to protect the cells and the transmitting fiber from the air flow generated by 350km/h high-speed trains, vibration, and long-term working under harsh open-air condition. For instance, stainless steel material is used for all parts, and thick pipe is employed for fiber protection. Because welding and drilling are not allowed on the track, Bolt tightening method was adopted for fixing the spring tie with the track. Fig. 9 and Fig. 10 are also shown the condition of the cells after 11 months using.

Fig.8 Actual installation on the bridge

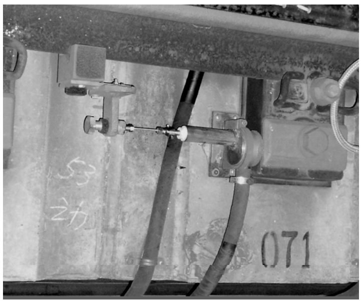


Fig.9 A track displacement cell

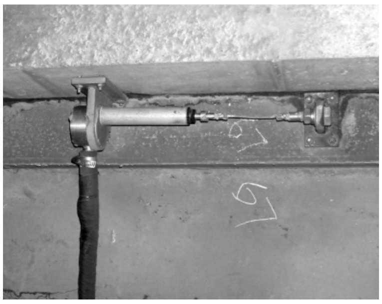


Fig.10 A slab displacement cell

Fig. 11 is displacement measuring results of a track during 75 days, they are randomly selected as examples. They show that during the hot summer, the displacement detected by a track cell was 9mm. And these displacements are of high correlation with daily environmental temperature change. The measuring results give correct displacement quantities of track and sleeper slab on the bridge. So this application of FBG sensing technology could help the management of high speed railway.

Comparing with traditional electric sensors, FBG has special advantage to measure the physical quantity for very long term under the harsh environment. Nowadays, the OFS technology develops quickly, lots of novel theory and method are being found. However, its application lags behind lab works. This application tries to explain that as long as people focus on engineering works, OFS engineering application is not a difficult job.

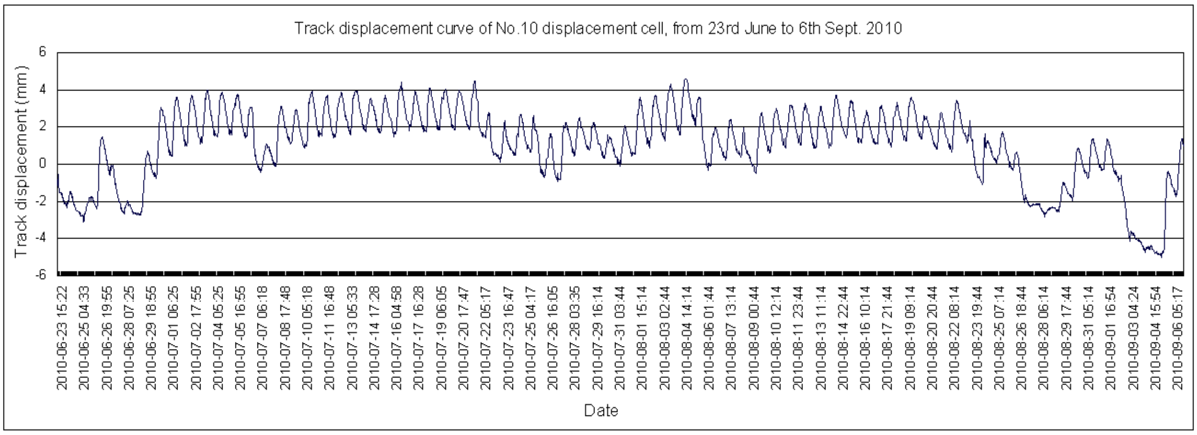


Fig.11 Curve of track displacement measured by the displacement cell No.10 in 75 days

Through cooperation with related institutions, series of engineering technical problems have been successfully solved; optical fiber sensing systems have been also applied to high speed railway safety monitoring, perimeter intrusion prevention and dam safety monitoring, etc.

4. OPTICAL FIBER SENSOR FOR TRANSFORMER TEMPERATURE MONITORING

The development of Smart Grid (SG) requires real-time and on-line monitoring of transformer.

Optical fiber sensor is the good choice to measure due to its characteristics of insulation and anti-electromagnetic interference. However many optical fiber temperature measurement technologies don't achieve good effect in the transformer, since the optical fiber sensor should be embedded in copper platoon of transformer winding when measuring temperature, and do not destroy the electromagnetic field distribution of transformer. Since the internal space of the transformer is limited, FBG and welding points can't take protective measures, and therefore is easily damaged. By cooperation with the electric power research institute as well as transformer manufacturer, mass fiber grating sensor array without welds has been successfully developed, which solves the engineering technical problems of FBG and welding points damage. Fiber grating sensor array and transformer inner wire are wounded at the same time in the transformer manufacturing process, obtained the transformer internal components temperature distribution, especially the winding hot temperature. 218 optical fiber Bragg grating sensors and 14 arrays of optical fibers are installed in key parts of transformer prototype, such as winding, strut, iron core, and so on. The phrase temperature variation curves of low-voltage module with different optical fiber grating sensor are as shown in Fig.12.

In Fig.12, the corresponding operation in a, b, c, d, and e time points are as follows: adjust loading current, down to the total loss, temporary outage, down to the rated current and stop loading. It can be found that each sensor temperature change rule is consistent, which can detect the change of load accurately and sensitively.

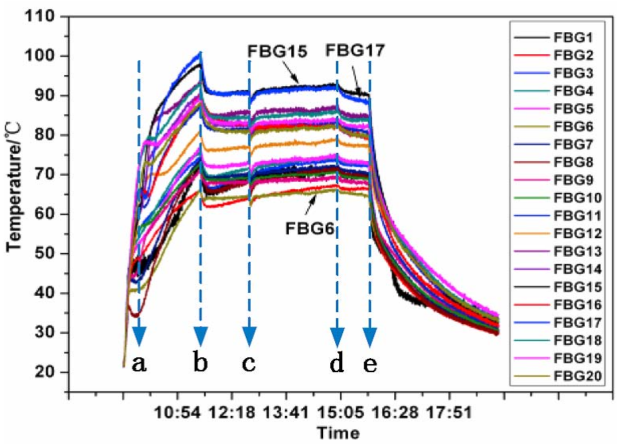


Fig. 12: Low-voltage winding a phrase temperature variation curves of buried optical fiber grating sensors

5. SUMMARY

This paper reviews on the main work in optical fiber sensing engineering experimental research and application at the National Engineering Laboratory for Optical Fiber Sensing Technology, Wuhan University of Technology. We emphatically introduce how to solve some of the different engineering technical problems according to different fields, and also introduce the applications of the research achievements in these fields. Development work and engineering application shows that optical fiber sensing technology and system is an ideal solution which applies to bridge, transportation, petrochemical, coal mine, the electric power and large projects in the field of harsh environment.

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