Research on the FBG stress automatic monitoring system of prestressed reinforcement Based on the virtual instrument technology

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ABSTRACT: The prestressed reinforcement plays an important role in the prestressed reinforcement concrete structure, so the monitoring of its prestress is significant. The special working surroundings make it difficult to monitor the prestress loss by using traditional sensing method. A long period and automatic monitoring method by adopting fiber Bragg grating (FBG) sensor arrays was proposed, and the corresponding theoretical analysis and experimental study were carried out. The experimental results indicate that the sensing system is suitable for the working surroundings of prestressed reinforcement, and has the characteristics of high linearity and good repeatability. The automatic monitoring system of FBG based on the virtual instrument technology was developed. Through serial communication, the functions of test instrument can be achieved by software controlling. The results can be saved in selected EXCEL file automatically, which help to dispose the sensing signals further, record the monitoring history and know the prestress variation in time. The perfected monitoring system is more suitable for practical application.

1 INTRODUCTION

Prestressed reinforcement is the key component to bear loads in prestressed reinforced concrete structure. The stress losses of the prestressed reinforcement resulted from all kinds of factors during construction and running stages will result in the decrease of prestress and consequently affect the security and reliability of the whole structure. The monitoring of prestress is the monitoring focus and difficulty of the whole prestressed reinforced concrete structure, and it has become the principal problem awaited to be resolved.

The working circumstance of prestressed reinforcement is special and different from others. It is imbedded in the concrete, and works in narrow space. The applied sensor should be small, not intervene the stretching process of prestressed reinforcement, and have the ability of obtaining the stress distribution along prestressed reinforcement. Moreover, the sensing system should be able to monitoring the stress of prestressed reinforcement real time and continuously during its lifespan, because the prestressed reinforcement will affect the carrying capacity of the whole structure once it is imbedded. When the traditional resistance strain gauge (RSG) is adopted, zero adjusting is always needed, and only the temporary and relative test can be achieved. If RSGs were adopted to measure the stress distribution along the prestressed reinforcement, numerous lead-out wires would be needed. The moisture and humidity during pouring will also affect the sensor's survival and normal work badly. FBG sensor not only has the advantages of small size, high precision, and immunity to electromagnetic interference, but also has its unique advantage. It can transform the variety of measurand to the shifting of FBG reflective wavelength, so the signal can't be interfered by the fluctuation of light source and the power loss of system. Furthermore the main predominance lie in its ability of wavelength division multiplexing (WDM) along single optical fiber [1,2], which provide conditions for the quasi-distributed monitoring of prestressed reinforcement.

Theoretical and experimental researches on the stress measurement of prestressed reinforcement adopting FBG sensors were carried out in the paper. Moreover, allowing for the special structure of prestressed strand, FBG pressure sensor located in the anchor position was also proposed. The signal demodulation of FBG sensor is a key issue [3], which has great influence on the practical applications. The multi-wavelength meter (MWM) is a multi-wavelength detection instrument. But it can only be operated manually, and cannot save the test results automatically, which make it difficult to record and save the test history. So it is inconvenient to use directly in practical application. By using the instrument controlling technology, the multi-wavelength automatic test system based on the virtual instrument technology was developed. The functions of MWM such as parameter setting, single/repeat measurement and the obtaining of test results can be achieved by software controlling. The test results can also be automatically saved in an EXCEL file named by user. Based on the virtual instrument technology, the test results can be disposed further by using mathematic analysis and signal disposing tools. It also helps to analyze and manage the history data and perfect the whole testing system.

2 SENSING THEORY OF FBG AND THE WDM SYSTEM

Based on the theory of mode coupling, when broadband light incidents FBG, only the light whose wavelength satisfies the Bragg condition can be reflected completely, and the other light will be transmitted through.

$$\lambda_B = 2n_{eff}\Lambda \qquad (1)$$

Where, λ_B represents the reflective wavelength, n_{eff} represents the effective refractive index, and Λ represents the grating period of FBG. The reflective wavelength will change due to the photo-elastic effect and the changing of grating period when the strain changes. The reflective wavelength will also change because of the thermo-optic effect and thermal expansion effect when the temperature changes. So the relationship among the wavelength, strain and temperature can be expressed as

$$\Delta\lambda_B / \lambda_B = (1-P_e)\varepsilon + (\xi_f + \alpha_f)\Delta T \qquad (2)$$

Where, P_e represents the photo-elastic coefficient, ξ_f represents the thermo-optic coefficient, and α_f represents the thermal expansion coefficient of fiber. The variation of measurand can be obtained by detecting the reflective wavelength of FBG.

The sensor multiplexing is the unique technology of optical fiber sensor, which makes it possible to test the distribution field along fiber length. On this condition the lead-out wires can be reduced, and the cost can also be cut down greatly. The WDM technology adopting wavelength coding has wide application foreground in the monitoring of great structure. The WDM sensing system is shown in Fig.1. The broadband light from ASE source is launched into the FBG array by a 3dB coupler, and the signals from the FBG array return to the MWM by the 3dB coupler again. Each FBG has its own reflective wavelength. The stress state of different test point can be obtained by monitoring the variation of reflective wavelength of each FBG.

Adopting the FBG WDM system to test the stress distribution is suitable for the working circumstance of prestressed reinforcement. While it is difficult for other sensors to realize the sensing purpose on the same condition. Single fiber is enough to transmit the signals from FBG array, which makes the monitoring of stress be achieved with the simplest setup and the least lead-out wire. So the FBG array has great advantages over the other sensors when distributed stress need be monitored. The diameter of optical fiber is 0.125mm, which makes it possible that the sensing element is bonded with prestressed reinforcement with little influence on its mechanical characteristics. The FBG can measure the stress absolutely due to its wavelength coding characteristics. It can also resist the interference of circumstance, and has good long-period stability. Accordingly it can be used to monitor the state of prestressed reinforcement real time and continuously.

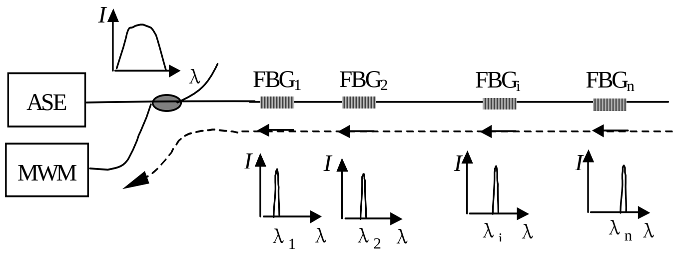

Fig.1 Wavelength division multiplexing system of FBG

3 FBG STRESS TESTING SYSTEM OF PRESTRESSED REINFORCEMENT

3.1 *The FBG stress test experimental system of prestressed steel reinforcement*

In order to validate the feasibility of FBG applying to the test of prestressed steel reinforcement, the FBG stress test of prestressed steel reinforcement were carried out and the experimental setup is shown in Fig.2. It is composed of the simulation stretching equipment, ASE broadband source, MWM and strain indicator. Two RSGs were bonded at opposite positions of steel bar to avoid the influence of deflection load, and one FBG was bonded in the groove on the steel bar with cyanoacrylate. Silicon was used to fill in the shallow groove to protect and airproof the optical fiber. In order to achieve better sensing characteristics and sensitivity, little tensile force was applied to the FBG, and the bare FBG was adopted to sense the strain of structure accurately. The coated transmission optical fiber is used to increase the security in operation. Turning the hand lever connected on the small gear makes two large gears turn, and then drive the lead strew turn. The moveable board moves along the lead strew, and consequently the loading and unloading can be achieved. The experimental data of 5 times loading cycle and the fitted curve obtained by the least square method are shown in Fig.3.

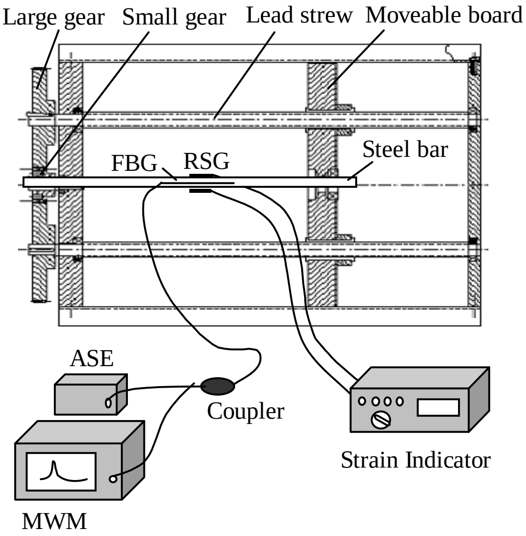

Fig.2 FBG stress experimental system of prstressed reinforcement

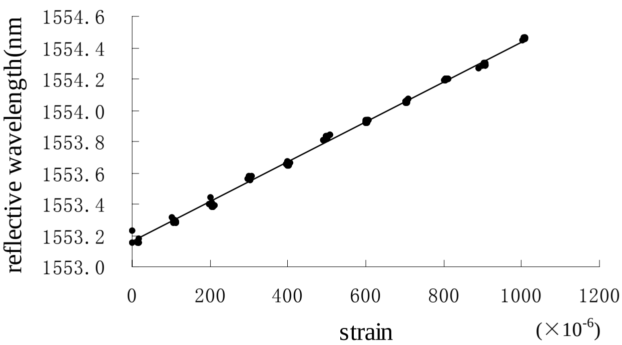

Fig.3 Experimental results of prestressed reinforcement under 5 times loading cycle

The initial reflective wavelength of FBG adopted in the experiment is 1553.206nm. The strain sensitivity obtained from the experimental data is 1.3pm/ με, which has good agreement with the calculated strain sensitivity 1.211pm/με. For the wavelength resolution of MWM is 1pm, the strain resolution of 0.77με can be obtained. Furthermore, the FBG shows good linearity and repeatability in the experiments. Initial strain occurs at the process of griping, for the mechanical loading equipment was adopted. Once the power was off abruptly or the test restarted some day, readjustment of zero for strain indicator should be carried out. So the initial strain of prestressed reinforcement will be lost. While the FBG senor can test the strain absolutely, and the actual strain of prestressed reinforcement can be obtained.

3.2 *The FBG stress senors of prestressed strand located in the anchor*

The special structure and complicated working state of prestressed strand make it difficult to measure its distributed stress. The prestressed strand is made up of several steel wires twisted together. As long as the sensor is contacted with certain wire directly, only the stress of the steel wire under test can be obtained. The methods of Stress wave [4] and electromagnetic stress sensor [5] are prone to be influence by electromagnetic interference, and the space problem of electromagnetic stress sensor is also difficult to resolve. Moreover, the squeeze and friction between the inner wire and outer wire will exist when the prestressed strand works, which makes it difficult for sensor to survive.

The measurement of whole stress of prestressed strand can be realized by placing the pressure FBG sensor under anchor located at the position ①, as shown in Fig. 4. The FBG pressure sensor under the anchor not only can monitor the prestress during stretching procedure, but also can continue carrying out the test work after stretching. The pressure sensor can be prefabricated, so it is suitable for field applications. Besides, the prestressed strands located in the inner cavity of jack cylinder are parallel with each other. Placing FBG sensor on this position can avoid the squeeze and friction between prestressed strands and concrete cavity. The sensor located at position ② as shown in Fig.4 can be used to monitor the actual stretch force, but it doesn't work when anchoring is finished because it cannot any longer sense the stress variation of prestressed strand located in the concrete cavity.

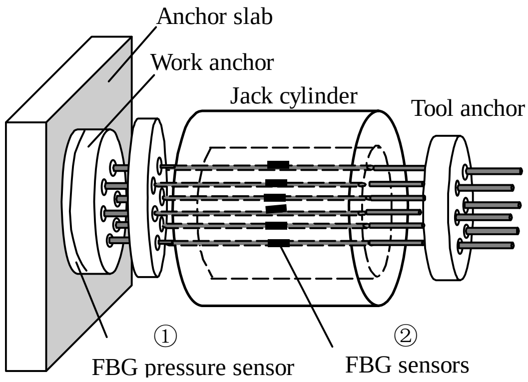

Fig.4 Stress testing system of prestressed strands located in anchor

4 AUTOMATIC TESTING SYSTEM OF FBG BASED ON THE VIRTUAL INSTRUMENT TECHNOLOGY

When matching FBG filtering method, F-P filtering method and interference demodulation method are used to demodulate FBG array, the complexity of demodulation system will increase along with the increasing of multiplexing FBG number. While the demodulation system adopting spectrum analysis method need not change along with the variation of multiplexing FBG number. The MWM is a reliable and sophisticated spectral measurement instrument. It can test the variation of multi-channel wavelength, and also can monitor the stability of peak wavelength and power. So the MWM is suitable for the detection of multiplexing FBG array. Compared with optical spectrum analyzer, the MWM has higher test precision and faster test speed. But if utilizing the MWM directly, only manual operation can be achieved, and the continuous record of test results is difficult to realize, which will bring much inconvenience to practical application.

The concept of virtual instrument was proposed by NI Co. in 1986, and later the integrity instrument system based on the virtual instrument technology come into being gradually. Here, choose the computer as the basic hardware platform, and the MWM with RS-232 serial port as instrument hardware equipment. The prestresss automatic testing system adopting FBGs located in single optical fiber is shown in Fig.5. In order to decrease the light loss, the circulator is adopted to replace 3dB coupler. The reflective light carried the prestress signals return to the MWM by circulator. By connecting with the virtual instrument, the MWM is controlled by computer. The automatic testing can be achieved through the serial port communication, which can help to analyze the results further, and inquire about the monitoring history.

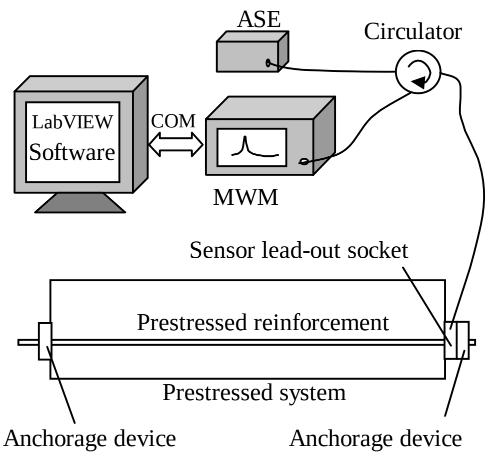

Fig.5 Automatic testing system of prestress adopting FBG array based on virtual instrument

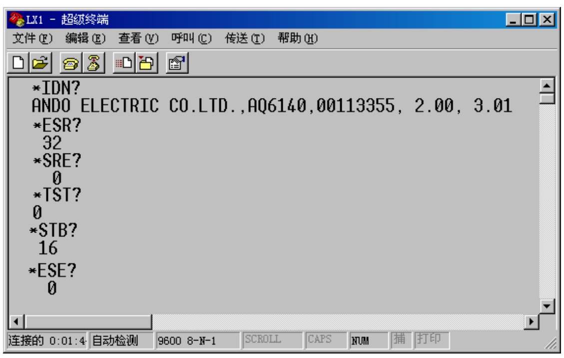

Fig.6 Retrieve the ID information of instrument and the status of registers by hyper terminal

First connect the serial ports of MWM with computer using cross cable, and then check the serial port preliminarily using the hyper terminal program of windows operating system, as shown in Fig.6. Make sure that the serial ports of instrument and computer work properly before programming with the virtual instrument software. The demands must be input manually one by one in the hyper terminal program, and the results cannot be disposed automatically. Full automatic operation cannot be achieved, so its application is limited.

Six VIs (Virtual Instruments) can be used to realize the serial communication in LabVIEW 7 Express. They are respectively VISA Configure Serial Port, VISA Write, VISA Read, VISA Bytes at Serial Port, VISA Serial Break and VISA Close. First initialize the serial port using VISA Configure Serial Port.vi, and set the parameters such as port number, baud rate, data bit, parity and stop bit. The serial port parameters of MWM and computer should match each other. Otherwise the normal communication will not be achieved. Initializing the serial port can make the MWM work in remote state, while pressing the local key on the front panel of MWM can make the instrument return to local state.

The remote demands of MWM can be divided into several types, as shown in Fig.7, such as query demands, parameter setting demands, single/repeat measurement demands, retrieving results demands and so on. First select the demands type, and then choose the proper demand to write. Inquire the bytes in the buffer before reading the results from instrument. The results data read out from the instrument directly are character type. Transform the character string to numerical data by using the character change subVI, and then save the results into a new or an existing EXCEL file by controlling the new/appending slide switch. Three FBGs connected in single fiber was test using the automatic testing system, and the front panels of return peak wavelength and peak power are shown in Fig.8, which were obtained by inputting the two demands ':MEAS:ARR:POW:WAV?' and ':MEAS:ARR:POW?' respectively.

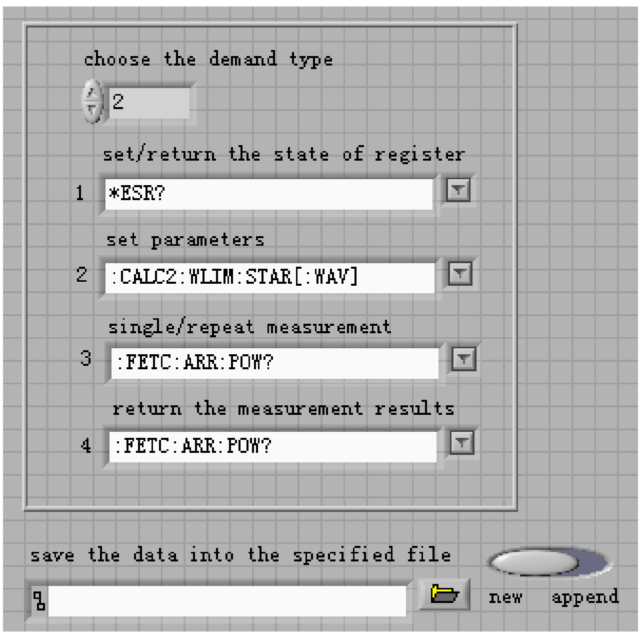

Fig.7 The front panel of virtual instrument about remote demands selection and file saving

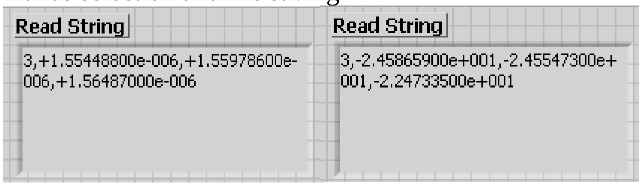

Fig.8 The return data of remote measure demands about peak wavelength and power

The results correspondent with every test can be saved in the selected EXCEL file sequentially, which helps to analyze the test results, and know the variety trend of measurand and its changing process. The whole test system of prestress was perfected, and the foundation was established to make it suitable for practical application much more. So the wavelength automatic test system of FBG based on the spectrum analysis and virtual instrument technology has great superiority in practical application.

5 CONCLUSIONS

Aiming at the prestress testing of traditional prestressed reinforcement, the distributed stress testing system by adopting FBGs connected in serial on single optical fiber was proposed. The experiment of prestress testing with one FBG bonded on the prestressed steel reinforcement was carried out on the simulative loading equipment. The results indicate that the FBG can be used to obtain the stress information without affecting the mechanical characteristics of prestressed reinforcement. It is suitable for being applied in the work circumstance of prestressed reinforcement. Moreover a FBG pressure sensor located under the anchor was also proposed. The RS-232 serial port of MWM was developed based on the virtual instrument technology. The automatic test of FBG reflective wavelength and automatic saving of the test results were achieved by software controlling. The test system of FBG wavelength division multiplexing system based on the MWM was perfected, and its universality and automaticity were also enhanced. It is more suitable for the long term monitoring of prestress, and has great application foreground.

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REFERENCES

Li Chuan, Han Xuefei, Zhang Yimo, et al. 2003. Sensing net of fiber Bragg grating via WDM technology[J]. *ACTA PHOTONICA SINICA*. 32(5) :542-545. (In Chinese)

Huang Junbin, Yin Jin, Zhang Xintian, et al. 2003. WDM distributed FBG sensor network[J]. *Journal of Transducer Technology*. 22(12): 9-11.

Zhang Ximing, Yu Youlong, Zhu Yong. 2002. Techniques for fiber Bragg grating sensor system demodulation[J]. *Optoelectronic Technology & Information*. 15(4): 17~20

Hung-Liang (Roger) Chen, Komwut Wissawapaisal. 2001. Measurement of tensile forces in a seven-wire prestressing strand using stress waves [J]. *Journal of Engineering Mechanics*. 127, 599-606.

Bouchilloux P, Lhermet N., Claeyssen F. 2000. Electromagnetic stress sensor for bridge cables and prestressed concrete structures [J]. *Journal of Intelligent Material Systems and Structures*. 10(5), 397-401.

C.C. Chan, W. Jin, M.S. Demokan. 1999. Enhancement of measurement accuracy in fiber Bragg grating sensors by using digital signal processing [J]. *Optics & Laser Technology*. 31: 299-307.