Study on the Mechanism of Static Comparison between Vibrating String Strain Gauge and Fiber Grating Strain Gauge for Bridge Structure Monitoring

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Abstract. The key component commonly used in strain monitoring is the strain sensor (strain gauge), which is usually embedded inside the measured object or installed on its surface to monitor the changes of corresponding variables for a long time. Therefore, the reliability, accuracy, consistency and stability of the strain sensor are important guarantees for the accurate measurement of strain. In order to monitor bridge changes more accurately, two strain sensors with a wide range of applications (i.e. vibration string strain sensor and fiber grating strain sensor) were selected for comparative analysis of the calibration model in the laboratory. We’ll use national standard of 6061 aluminum alloy cylindrical bar and fix two strain sensors separately in the symmetric position. In order to eliminate the detection error caused by the current sensor detection when the metering clamping device and the strain sensor are under stress, 0-100kn compression test was conducted on the bar by using the superposition force standard machine. The device collects data of the two sensors, conducts data regression analysis, obtains the new model and hence conducts data analysis and comparison. The results show that the accuracy of the model is much higher than that of the strain sensor. The results of this study provide technical support for the development of real-time bridge detection technology and the realization of rapid calibration and detection of strain monitoring sensors used in the transportation industry before installation.

Key Words. traffic measurement, fiber grating, vibrating string strain gauge, Matlab, data model

1. Introduction

In industries and fields such as bridges, tunnels, oil pipelines and aerospace, long-term monitoring of structural health is required, especially the strain monitoring within the structure is very important [1-4]. Common strain sensors include vibrating string strain gauge, resistance strain gauge and fiber grating strain gauge, etc. [5] Their performance testing is very important. With the improvement of the manufacturing quality of strain gauge, its measurement accuracy becomes higher and higher, and the calibration measurement characteristics are gradually improved. In many fields, the need for high-precision strain gauge calibration becomes more and more urgent [6]. In order to monitor bridge
changes more accurately, this paper established a more accurate monitoring model by comparing the fiber Bragg grating strain sensor and the vibrating string strain sensor bridge health monitoring calibration model. This provides technical support for the development of real-time bridge detection technology and the realization of rapid calibration and detection of strain monitoring sensors used in the transportation industry before installation.

2. The Working Principle of Vibrating String Strain Gauge and Fiber Grating Strain Gauge

2.1 Theoretical Model of Vibrating String Sensor

The vibrating string sensor works in the way of steel string vibration, and the force is represented by the change of vibration frequency, the actual output frequency signal is delivered. Therefore, there are no problems that strain gauge must be calibrated on the spot, signal drifts and poor durability for long use. Aluminum bar works well. It solves the shortcoming of strain gauge’s instability in long-term use. It is currently used on a large scale in bridge monitoring.

The vibration string sensor has good measurement characteristics. It can achieve less than 0.1% in non-linearity, 0.05% in sensitivity and less than 0.1%/10℃ error in temperature. After the strain gauge is manufactured, its steel string has a certain initial tension $T_0$, so it has an initial frequency $F_0$. When the strain gauge is installed, the tension of the vibrating string changes with the deformation. The strain can be measured by the tension of the vibrating string.

2.2 The Working Principle of Fiber Grating Strain Gauge

Fiber Bragg Grating Sensor (Fiber Grating Sensor) is a kind of optical Fiber Sensor and it is based on Fiber Bragg Grating sensing process. It is a kind of wavelength modulated fiber optic sensor, which obtains sensing information by modulating the wavelength of fiber Bragg with external physical parameters. Fiber Bragg grating sensors can directly measure physical quantities such as temperature and strain. Since the wavelength of the fiber Bragg grating is sensitive to both temperature and strain, that is, temperature and strain cause the shift of the coupled wavelength of the fiber Bragg grating, it is impossible to distinguish between temperature and strain by measuring the shift of the coupled wavelength of the fiber Bragg grating. Therefore, to solve the problem of cross sensitivity and to realize the discriminating measurement of temperature and stress is the premise of sensor application. The discriminating measurement of temperature and stress is realized by measuring the stress and temperature changes through certain technology. The basic principle of these technologies is to use two fiber Bragg gratings with different temperature and strain response sensitivity to form double grating temperature and strain sensor. By determining the temperature and strain response sensitivity coefficient of two fiber Bragg gratings, the temperature and strain can be solved by using two binary primary equations. There are two kinds of measurement techniques: multi-fiber grating measurement and single-fiber grating measurement.

3. Test Plan

In this test, the superposition force standard machine, which has been approved by the national metrology institute of China, is adopted, and the sinusoidal strain sensor of manufacturer A and fiber grating sensor of manufacturer B are widely used in the domestic testing market.

In the 6061 T6 aluminum rod, a vibrating string-type strain sensor and a fiber Bragg grating sensor are respectively fixed at both ends of the penetrating nut. See figure 1. The superposition force standard machine was used to conduct the pressure test on the aluminum rod. The aluminium index show of the table 1. The test was divided into three groups according to the test pressure, namely, 50KN group, 75KN group and 100KN group.

The test pressure of 50KN group was determined according to the formula $F_\text{in} = 5 \times (n-1)$ (1 in the formula represents the 50KN test group; $N = 1,2,3,4,5,6,7,8,9,10,11$, representing the test level of this group; $F$ stands for test horizontal pressure, unit KN)
In the pressure test at each pressure level, the pressure loading of different types of sensors lasted for 120s, the test was repeated for 10 times, and the test data was collected.

![Diagram of experimental equipment](image)

**Figure 1.** Diagram of experimental equipment

| Tensile strength $\sigma_b$ | yield strength $\sigma_{0.2}$ | Elongation $\delta_5$ (%) | elastic coefficient | Ultimate yield strength | Bearing Yield Strength | fatigue strength |
|----------------------------|-------------------------------|--------------------------|---------------------|------------------------|-----------------------|-----------------|
| $\geq$ 180MPa             | $\geq$ 110MPa                | $\geq$ 14                | 68.9GPa             | 228MPa                 | 103MPa                | 62.1MPa         |

Note: longitudinal mechanical properties of bar materials at room temperature

**4. Test Results and Analysis**

In this study, MATLABR2014 software was used to analyze the test data, and Origin8.5 was used to draw the graph. Figure 2, 3 and 4 are data fitting curves of fiber Bragg grating sensors (50KN group, 75KN group and 100KN group). Figure 5, 6 and 7 respectively represent the data fitting curves of the vibrating chord sensor groups of 50KN, 75KN and 100KN. In this study, regression analysis was conducted on the results of the two sensors to obtain the new models Y1 and Y2.

![Data graph of 50kn test group](image)
Figure 3. Data graph of 75kn test group

Figure 4. Data graph of 100kn test group
Figure 5. Fitting curve of fiber grating 50kn

Figure 6. Fitting curve of fiber grating 75kn

Figure 7. Fitting curve of fiber grating 100kn
Figure 8. Fitting curve of vibration chord 50kn

Figure 9. Fitting curve of vibration chord 75kn

Figure 10. Fitting curve of vibration chord 100kn
In this paper, Origin is used to draw data graphs of two kinds of sensors under three pressure value tests, as shown in figure 2-4. At the same time, the least square method in MATLAB software was used to fit the test data curves of the two sensors under three pressure levels, as shown in figure 5-10.

It can be seen from the comparison of the above figures that the data of the fiber Bragg grating sensor increases with the increase of the force value, which is monotonically proportional. Whereas the numerical value of the vibrating chord sensor and force value do not increase monotonically. Therefore, the fiber Bragg grating sensor can characterize the change of strain variables more accurately than the vibrating chord sensor.

The curve fitting indexes of the experimental model were obtained through the least square analysis, as shown in table 2. SSE in the table is the sum of squares due to error; MSE is Mean squared error: mean square deviation, variance; RMSE: Root mean squared error; R-square: Coefficient of determination; Adjusted R-square: degree-of-freedom adjusted coefficient of determination.

|                  | Fiber grating sensor | vibrating chord sensor |
|------------------|----------------------|------------------------|
| 50KN test group  | SSE                  | 20.79                  |
|                  | R-square             | 0.9998                 |
|                  | Adjusted R-square    | 0.9991                 |
|                  | RMSE                 | 3.224                  |
| 75KN test group  | SSE                  | 197.2                  |
|                  | R-square             | 0.9992                 |
|                  | Adjusted R-square    | 0.9992                 |
|                  | RMSE                 | 7.022                  |
| 100KN test group | SSE                  | 6.502                  |
|                  | R-square             | 0.9996                 |
|                  | Adjusted R-square    | 0.9998                 |
|                  | RMSE                 | 1.472                  |

It can be seen from table 1 that the data of the 75kn test group of fiber Bragg grating sensor are best fitted by the least square method.

The fitting curve expression is:

\[ f(x) = -2.461 \times x^8 + 13.79 \times x^7 + 3.198 \times x^6 - 37.6 \times x^5 - 40.57 \times x^4 + 131.9 \times x^3 - 52.72 \times x^2 - 413.5 \times x + 137.1 \]

5. Conclusion
Aiming at the difficulty of on-line calibration of strain gauge in practical use, a static comparison method based on high-precision force standard machine is proposed. Taking the micro deformation of the structure’s characteristic position as the research scene and the uniform metal material as the medium, two kinds of equidistant sensors with different working principles were compared and verified. Conclusions are as follows: 1) The accuracy and real-time of the calibration model of the fiber grating strain sensor is much higher than that of the vibrating string strain sensor. It can also be understood that the vibrating string type sensor needs a long time to stabilize after each load to reduce the data instability caused by the tension deformation of the steel string itself. 2) Fiber Bragg grating technology has a good sense of the environment temperature, and has a good temperature compensation system. Thus, the data are more stable and reliable. Fiber Bragg grating strain gauge is more suitable for dynamic real-time acquisition and can be used as a reference sensor for on-site calibration. This study provides technical support for the development of bridge structure online comparison technology in the future and the rapid calibration and detection of strain monitoring sensors used in the transportation industry before installation.

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