Development of Optical Fiber Strain Calibration Device

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Abstract. The Brillouin distributed sensing system is sensitive to the crossover between strain and temperature. The temperature and strain can be measured simultaneously through decoupling. Therefore, a method of calibrating fiber strain by grating ruler is proposed, the decoding circuit of grating ruler is designed, and the calibration device of optical fiber strain is built. The experimental results show that the uncertainty reaches 5.90 μm (k = 2) in the range of 0 ~ 1000 μm, and the measurement of optical fiber strain can be traced back to the national length standard.

1. Introduction
The Brillouin distributed optical fiber sensing system is widely used in the monitoring of working conditions of major projects such as railways, submarine optical cables, bridges and tunnels due to its advantages of long measuring distance, strong anti-interference, and long service life. The measurement principle of the Brillouin distributed optical fiber sensing system is to use the sensitive effect of Brillouin frequency shift to strain to change the measured strain physical quantity directly into an optical quantity for measurement. This measurement method has the advantages of zero drift, long-term stability, etc [1-3]. Brillouin scattering light signal is cross sensitive to temperature / strain, using a single fiber structure, the temperature/strain separation monitoring is realized by detecting the Brillouin signal frequency shift and power at the same time, however, the power detection is easy to be disturbed and has poor stability. Moreover, since the sensitivity coefficient of temperature to Brillouin signal frequency shift and power is far greater than the strain sensitive coefficient, the error of frequency shift and power detection will have a greater impact on the strain detection results. Therefore, in order to realize the detection of corresponding variable signal, the requirements for the device are very high. Therefore, a high-precision strain measurement device is required to calibrate the strain measured by the Brillouin sensor measurement system. At present, temperature coefficients are often calibrated using methods such as thermostats. Regarding the calibration of optical fiber strain coefficients, there are few related reports. In 2006, Suo W.B. et al [4] proposed the method of equal strength beam to calibrate the strain coefficient of optical fiber. By affixing the optical fiber to the equal strength beam with strain gauges, the strain of the optical fiber is obtained by averaging the strain values the strain of the points attached to the strain gauge, and then the strain of the optical fiber is obtained. In the literature, due to the number of strain gauges and the pasting process, the strain value read by the strain gauge is not necessarily the true strain value of the optical fiber. In addition, the uncertainty analysis of the system is not proposed in the literature, so that the measured value is not credible degree. In 2013, Yan J.S. et al [5] designed a fiber optic strain coefficient calibration
system based on stretching devices. By pasting the fiber under test on the stage and the fixture table respectively, the initial length of the fiber is measured with a length ruler. After the fiber is stretched, the amount of fiber stretch is measured from the reading on the stage. In this method, it is cumbersome to paste the optical fiber through glue during the measurement process, which is not conducive to batch operation. In addition, the measurement accuracy of the optical fiber strain using the stage is limited. This article combines the physical meaning of the strain variable, converts the fiber strain to the fiber stretch and then measures it. Based on this, a method for detecting the fiber strain by the grating ruler is proposed, and a fiber strain calibration device is built.

2. Device scheme design

2.1. Technical indicators
Range: 100 ~ 1000 μm;
Uncertainty: 10 μm (k = 2).

2.2. Overall scheme design
As shown in figure 1, the device is composed of grating ruler, precision displacement slide table, optical fiber holder, motor, reducer, measurement and control circuit and measurement and control software. Two optical fiber grippers are respectively fixed on the moving slide block and the clamping table through the optical fiber holder fixing parts, which are used to fix the bare optical fiber. One end of the single-mode bare optical fiber is fixed by the optical fiber holder on the moving slider, and the other end is fixed by the optical fiber holder on the fixture table. By changing the distance between the fixed base and the fixture table by moving the base, the installation and measurement requirements of different lengths of optical fiber to be measured can be met. The grating ruler fixing parts fix the grating ruler reading head on the movable sliding table. The grating ruler reading head is used to read the relative displacement of the sliding table. The stepper motor drives the screw to rotate to make the moving slider move axially, and then drives the bare optical fiber to produce a certain amount of relative displacement $\Delta l$, so as to achieve the effect of applying the standard strain to the optical fiber.

![Figure 1. Schematic Design of optical fiber strain calibration device](image)
The optical fiber strain calibration device is shown in figure 2. The whole set of device is composed of electric control box, sliding table and optical fiber holder.

![Physical diagram of optical fiber strain calibration device](image)

3. Development of calibration device

3.1. Mechanical selection

Due to the short movement distance of the calibration device each time, using the motor to drive the sliding table directly will easily lead to excessive movement of the slide table, which will break the optical fiber, and the output of the motor is also unstable. Therefore, a precision reducer is added between the motor and the sliding table, so that the sliding table can move in a small distance and its stability can be guaranteed. In this paper, a precise planetary reducer with a reduction ratio of 20:1 is used. According to the literature research, the optical fiber fixation methods designed before are all fixed with glue, which is cumbersome and not conducive to batch operation. In this paper, the optical fiber holder is selected to fix the optical fiber to be tested. By adjusting the screw of the optical fiber holder, the clamping force of the optical fiber can be controlled, and the optical fiber to be tested can be easily replaced. The optical fiber holder is shown in figure 3.

![Optical fiber holder](image)

The grating ruler is used as the core detection sensor in the calibration device. KA300-70-1 of Guangzhou XinHe Sino is selected, and its resolution can reach 1 μm. The mechanical selection parameters of calibration device are shown in Table 1.
Table 1. mechanical device selection table

| Name                        | Mode                | Related technical parameters |
|-----------------------------|---------------------|------------------------------|
| Precision electric slide    | HT110BX05-57W-50L   | Accuracy of repeated position: 0.02mm |
| Xinbao planetary reducer    | PL60                | Reduction ratio: 20:1         |
|                            |                     | Accuracy: 5′                  |
| Grating ruler               | KA300-70mm-1        | Resolution: 1 μm              |
|                            |                     | Accuracy: 3 μm                 |
| Optical fiber holder        | Y102FA              | Clamping diameter: 0.25 mm    |

3.2. Hardware design

The hardware circuit of the device is mainly composed of STM32 microcomputer, grating ruler, motor driver, motor, etc. The hardware block diagram of the device is shown in figure 4. STM32 [6-8] is the core processor of the hardware circuit, which controls the motor movement and reads the data output by the grating ruler decoding circuit [9-10], through which the corresponding data processing is done, and the final measurement results are displayed on the display screen. When the sliding table moves, the output signal of grating ruler is TTL orthogonal signal, which is transmitted to grating ruler decoding circuit through optocoupler isolation circuit. After decoding, the signal is transmitted to voltage protection circuit. After converting 5V voltage to 3.3V voltage, it is output to IO port corresponding to STM32 single chip microcomputer to read grating ruler data. Although some IO ports of STM32 single chip microcomputer can withstand 5V voltage, in order to prevent the voltage higher than 5V when the power supply is cut off, protective measures are taken.

![Figure 4. hardware circuit block diagram of the device](image)

3.3. Software design

The software in the device mainly includes human-computer interaction interface software and control data processing software. The 4.3-inch capacitive touch screen is used as the human-computer interaction platform. Compared with the physical key interaction, the physical key has mechanical contact, which is easy to damage and failure, while the touch interaction is more convenient, accurate and fast, and more durable, which can improve the service life of the whole device. The program is written in C language by keil5 software. The human-computer interface of the calibration device is shown in Figure 5. There are three icons in the main interface, which are "calibration", "traceability" and "setting". When the icon is touched, the corresponding interface can be entered for corresponding parameter setting and operation. The calibration interface can calibrate the optical fiber strain measured by Brillouin distributed optical fiber system; after the calibration device is used for a period
of time, the device also needs to be calibrated, so the traceability interface is designed to realize the calibration of the device and ensure its accuracy; the setting interface can realize the setting of the test fiber length value.

![Main interface](image1)

![Calibration interface](image2)

![Traceability interface](image3)

![Setting interface](image4)

Figure 5. Human computer interface

4. Analysis of the performance and uncertainty of the calibration device

The source of uncertainty of the calibration device mainly includes the uncertainty component introduced by the grating ruler itself, the uncertainty component introduced during the upper level traceability, and the assembly error introduced during installation.

(1) Uncertainty introduced by the calibration device itself $u_1$

At a laboratory temperature of 22°C and an ambient relative humidity of 60%, three repetitive measurement experiments were carried out. The experimental data obtained are shown in Table 2. The uncertainty introduced by the measurement repeatability of the calibration device belongs to the type A uncertainty in the evaluation of the uncertainty, which is obtained by using the Bessel formula.

Table 2. Calibration device repeatability experiment data

| Displacement point /μm | The first time /μm | The second time /μm | The third time /μm | Mean value /μm | Standard deviation /μm |
|------------------------|-------------------|--------------------|--------------------|---------------|------------------------|
| 100                    | 100               | 99                 | 99                 | 99.3          | 0.58                   |
| 200                    | 199               | 200                | 198                | 199.0         | 1.58                   |
| 300                    | 297               | 298                | 301                | 298.7         | 2.08                   |
| 400                    | 399               | 397                | 395                | 397.0         | 2.0                    |
| 500                    | 501               | 498                | 503                | 500.7         | 2.12                   |
| 1000                   | 1003              | 998                | 998                | 999.7         | 2.89                   |

It can be seen from Table 2 that the calibration device has uncertainty introduced by measurement repeatability $u_{11}=2.89$μm.

The scale data is displayed on the touch screen, and the minimum display digits of the value are single digits, so the resolution of the calibration device is 1μm, and the expansion factor $k=2$, so the uncertainty introduced by the resolution is $u_{12}=0.5$μm.

Therefore, the uncertainty $u_1$ introduced by the calibration device itself is:

$$u_1 = \sqrt{u_{11}^2 + u_{12}^2} = \sqrt{2.89^2 + 0.5^2} = 2.93\mu m$$

(2) Uncertainty introduced by superior traceability $u_2$
The calibration device uses a laser interferometer with an uncertainty of 0.5μm (k=2) to perform the calibration test, so the uncertainty u2 introduced by the upper level traceability is: 0.25μm.

(3) Abbe error introduced by fixed position of optical fiber and grating ruler u3

If the axis of the stretched fiber and the grating ruler are not parallel, Abbe error is introduced during the calibration of the fiber strain. In this paper, the parallelism of the fiber holder and the grating ruler is tested by using a digital dial indicator to check that the parallelism is 20μm, so the uncertainty u3 introduced by Abbe error is: 0.20μm.

Therefore, the combined standard uncertainty uc of the calibration device is:

\[
uc = \sqrt{u_1^2 + u_2^2 + u_3^2} = \sqrt{2.93^2 + 0.25^2 + 0.20^2} \approx 2.95\mu m
\]

Taking the expansion factor k = 2, the calibration device expansion uncertainty U is:

\[
U = k \times uc = 2 \times 2.95 = 5.90\mu m
\]

It can be seen that the uncertainty of the developed calibration device meets the design index of the device.

5. Conclusion

The optical fiber strain calibration device developed in this paper can calibrate the optical fiber strain in the Brillouin distributed sensing system and convert it into a length parameter traceable to the national benchmark. It is proved by experiments that in the range of 0~1000μm, the uncertainty reaches 5.90μm (k=2), which has good stability and accuracy. It is of great significance to the reliability of the measurement results of the Brillouin distributed sensing system.

Acknowledgments

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