Design and realization of high precision FBG rain gauge based on triangle cantilever beam and its performance research

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A novel fiber Bragg grating (FBG) rain gauge is proposed in this paper to achieve high precision rainfall measurement. One core sensitive FBG, a temperature compensation FBG and a mechanical transition system construct this novel FBG rain gauge. Sensing principle of this FBG rain gauge is explained in detail, and its theoretical calculation model is also established, which shows that the relationship between center wavelength of sensitive FBG and external rainfall has very good linearity. To verify its detection performance, the calibration experiment on one prototype of this FBG rain gauge is carried out. After experiment data analysis, the detection precision of this FBG rain gauge is 15.4 μm which is almost two orders of magnitude higher than that of the existing rainfall measurement device. The experimental data confirm that this FBG rain gauge can achieve rainfall measurement with high precision.
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Accurate rainfall measurements play important roles in hydrological applications, and particularly in an urban context. The most commonly used rainfall measurement devices are tipping bucket rain gauges, disdrometers, weather radars and (passive or active) sensors onboard satellites[1]. A rain gauge typically collects rainfall at ground level over a circular area with a diameter of 20 cm, and the sample area of operational disdrometer is roughly 50 cm^2, whereas a radar scans the atmosphere over a volume whose projected area is roughly 1 km^2 (for standard C-band radar operated by most of the western Europe meteorological national services)[2]. The measuring area limitations of tipping bucket rain gauge and disdrometer make them hard to be used in large scale rain gauge measurement. Although the weather radar provides rainfall data with relatively high spatial and temporal resolution, the data are subject to several sources of errors[3]. So the spatial and temporal distribution measurement and the prediction with high precision of rainfall are still key challenges in hydrology[4].

Due to the unique advantages of fiber Bragg grating (FBG), such as immunity to electromagnetic interference, compact size, resistance to corrosion, high sensitivity, long distance sensing and the ability to be embedded into composites with minimum structural degradation, optical fiber strain sensors are widely used in many applications[5-8]. They are also used to measure the stability of deep landslides caused by rainfall[9].

Based on the above statement, an FBG rain gauge is proposed, which can achieve large scale rainfall measurement with high precision. Due to the optical signal of FBG demodulated by external rainfall, the biggest advantage of this rain gauge is that it does not need any waterproof processing which has to be done in electrical rain gauge. Water gathering element, measuring transfer element and triangular cantilever beam construct the mechanical transition system which establishes the relationship between rainfall and center wavelength shift of FBG. According to the basic mechanical knowledge and the optical fiber theory, the theoretical calculation model of the relationship is built up. Further, the calibration experiment on one prototype of this FBG rain gauge is also carried out to obtain its measuring performance. After experimental data analysis, the measuring accuracy of this FBG rain gauge is obtained as 15.4 μm. So this FBG rain gauge can be used in rainfall measurement with high precision, and has practical applications in large scale rainfall detection.

The mechanical transition system of this FBG rain gauge consists of water gathering element, measuring transfer element and triangular cantilever beam just as shown in Fig.1. The working principle of the mechanical

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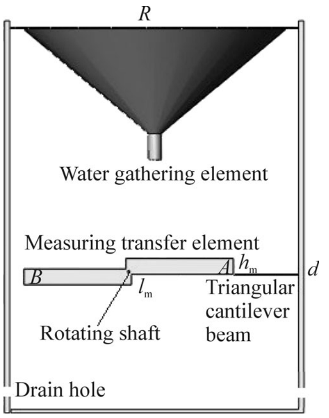
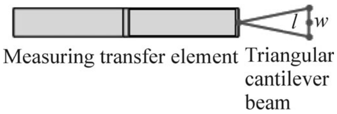
transition system is explained as follows.



(a) Cutaway view



(b) Top view of measuring transfer element and triangular cantilever beam

Fig.1 Schematic diagram of the mechanical transition system

Step 1: As the rainwater is collected by water gathering element into the measuring transfer element, the measuring transfer element will be rotated, which is caused by rainwater gravity.

Step 2: The rotation of measuring transfer element leads to the bending of the triangular cantilever beam.

Step 3: Beam bending can change the wavelength of FBG which is adhered on the surface of cantilever beam.

Step 4: With the increase of rainfall, growing beam bending will lead to separating *A* point of measuring transfer element and triangular cantilever beam.

Step 5: After the rotation of measuring transfer element, *B* point will touch the cantilever beam.

As the rainfall continues, the mechanical transition system repeats the process from step 1 to step 5. In conclusion, the rainfall can be measured by FBG center wavelength shift.

Assuming that the external rainfall is *P*, the rain gravity *F* loaded on the measuring transfer element can be expressed as

$$F = \rho P \pi R^2 g \ , \tag{1}$$

where ρ is the density of the rainwater, and *g* is the gravitational constant.

Surface strain ε and deflection angle at end section of cantilever beam θ_B under external load *F* can be expressed as

$$\varepsilon = Flh/3EI = 4Fl/Ebh^2 \ , \tag{2}$$

$$\theta_B = Fl^2/2EI = 6Fl^2/Ebh^3 \ , \tag{3}$$

where *E* and *I* are the elastic modulus and the section inertia of cantilever beam.

As the measuring transfer element detaches with the triangular cantilever beam, and according to Fig.1(a), the gravity of rainfall F_d can be expressed as

$$F_d = Ebh^3 h_m / 6 l_m l^2 \ . \tag{4}$$

So the surface strain ε_d under this condition is

$$\varepsilon_d = 2hh_m / 3ll_m \ . \tag{5}$$

The FBG which is adhered on the surface of cantilever beam has wavelength selection characteristic, i.e., only the wavelength which satisfies the Bragg condition is affected and strongly back-reflected. The reflected center wavelength λ_B can be expressed as[10]

$$\lambda_B = 2 n_{eff} \Lambda \ , \tag{6}$$

where n_{eff} is the effective index of refraction, and Λ is the grating periodicity of the FBG.

As the external temperature is kept stable, the general relationship between strain ε and wavelength shift $\Delta\lambda_B$ can be described as[11,12]

$$\frac{\Delta\lambda_\varepsilon}{\lambda_B} = (1 - p_e)\varepsilon \ , \tag{7}$$

where p_e is optical elasticity coefficient of fiber, and its theoretical value is 0.22.

So the relationship between rainfall *P* and center wavelength shift λ_{BE} of FBG can be expressed as

$$\Delta\lambda_{BE} = 4(1 - p_e)\lambda_B l / Ebh^2 \cdot \rho \pi R^2 \cdot P \ . \tag{8}$$

According to Eq.(8), we can obtain that the relationship between rainfall and center wavelength shift of FBG is linear as the geometrical parameters of this FBG rain gauge are determined. Once the surface strain is bigger than ε_d, all the calculation steps should be repeated.

To verify the measuring performance of this FBG rain gauge, a prototype is designed and manufactured. The prototype is shown in Fig.2. The function of micropores in the water gathering element as shown in Fig.2(b) is to catch the impurities in rainfall.

(a) Side view (b) Top view

Fig.2 Prototype of the proposed FBG rain gauge

The main material of this prototype is stainless steel. Due to its outstanding mechanical properties, low weight and corrosion resistance[13,14], the carbon fiber composite board is chosen as the material of triangular cantilever beam. The core sensitive element of FBG included in this prototype is adhered on the back surface of the triangular cantilever beam. In this way, FBG can not be influenced by the rotation of measuring transfer element. The basic geometrical parameters of this prototype are shown in Tab.1.

Tab.1 Geometrical parameters of the FBG rain gauge prototype

Symbol	Parameter	Value
E	Elasticity modulus of triangular cantilever beam	1.65×10^5 MPa
l	Length of triangular cantilever beam	25×10^{-3} m
b	Fixed end of triangular cantilever beam	10×10^{-3} m
h	Height of triangular cantilever beam	0.3×10^{-3} m
ρ	Density of rainwater	1×10^3 kg/m^3
R	Radius of water gathering element	50×10^{-3} m
l_m	Length of measuring transfer element	40×10^{-3} m
h_m	Height of measuring transfer element	2×10^{-3} m
λ_{BE}	Initial center wavelength of sensitive FBG	1 535.996 9 nm
g	Gravitational constant	9.8 N/kg

The schematic diagram of calibration experiment platform is shown in Fig.3. MOI SM125 with the demodulation wavelength range of 1 510–1 590 nm and the precision of 1 pm is chosen as the optical fiber interrogator in the platform.

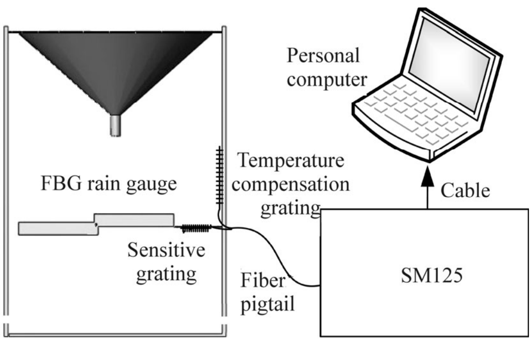


Fig.3 Schematic diagram of the calibration experiment platform

Before the beginning of the calibration experiment, the personal computer acquires the center wavelength of FBG for almost 1 min, and the mean value of the acquired data is selected as its initial center wavelength. The tap-water is added into the water gathering element to simulate the rainfall process until the measuring transfer element rotates and the center wavelengths of FBG are all saved in this adding process. The quantity of tap-water is controlled by 1 mL medical syringe. After adding 1 mL tap-water, the center wavelength of FBG is saved by personal computer for about 1 min. The mean value of these data is chosen as effective data corresponding to tap-water under this condition. The calibration experiment is stopped as the rotation of measuring transfer element happens. All these experimental processes are repeated four circulations. Fig.4 shows the wavelength shift of FBG with adding tap-water in the first circulation.

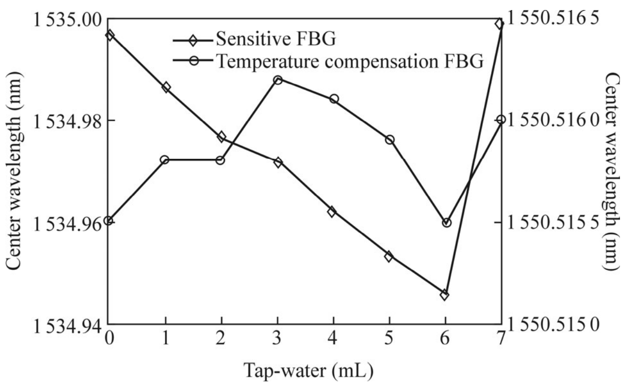


Fig.4 Center wavelength shifts of FBGs with adding tap-water in the first circulation

The temperature compensation FBG is not affected by external rainfall, which means that the detection precision of this rain gauge will not be influenced by temperature. The least square method is introduced to obtain fitting curves between center wavelength shift of FBG λ_B and the quantity of tap-water P_E. The formula of fitting curve is $\lambda_B=-0.008\,3\times P_E+1\,535$, where the linearity of the formula is $R^2=0.994\,8$. So the measuring coefficient of this FBG rain gauge is 8.3 pm/mL. Using the same data processing method, the measuring coefficients in the other three circulations are 8.1 pm/mL, 8.4 pm/mL and 8.3 pm/mL, respectively. So the mean value of these measuring coefficients is chosen as the final coefficient of this FBG rain gauge, and its value is 8.275 pm/mL. Using the theoretical calculation model, the detection coefficient is 7.91 pm/mL. The difference between theory calculation value and calibration experimental value may be mostly caused by the elastic modulus of cantilever beam. From Fig.4, we can obtain that the center wavelength of sensitive FBG returns back to the initial wavelength after adding 6 mL tap-water. This phenomenon indicates that the measuring transfer element rotates in the process of adding 7 mL tap-water. This variation tendency matches well with the theory calculation model in which the measuring transfer element will be rotated after adding 6.06 mL tap-water. Considering the demodulation precision of SM125 (1 pm) and the radius of water gathering element (50×10^{-3} m), the rainfall detection precision of this FBG rain prototype is calculated, and its value is 15.4 μm. All these data confirm that this FBG rain gauge can achieve precision rainfall measurement, and has certain practical applications.

To obtain high precision rainfall measurement, an FBG rain gauge is proposed in this paper. This FBG rain gauge consists of a core sensitivity element FBG, a temperature compensation FBG and a mechanical transition system which contains the water gathering element, the measuring transfer element and the triangular cantilever beam. Due to the unique advantages of FBG, this rain gauge does not need to do any waterproof process which must be done in some electrical rain gauge. The theory calculation model of this FBG rain gauge is established by using basic mechanical knowledge and optical fiber theory. The theory calculation results show that the relationship between rainfall and center wavelength shift of FBG is linear as the geometrical parameters of this FBG rain gauge are determined. To verify its detection performance, a prototype of this FBG rain gauge is fabricated, and the calibration experiment on this prototype is also carried out. Through experiment data analysis, the measuring accuracy of this FBG rain gauge is 15.4 μm. The results of calibration experiment confirm that this FBG rain gauge can achieve rainfall measurement with high precision.

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