Measuring vibration by using fiber Bragg grating and demodulating it by blazed grating

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A method of measuring vibration by using fiber Bragg grating (FBG) and demodulating the spectrum by blazed grating is introduced. The sensor system is made of a simple supported beam with a FBG adhered to its upper surface. A blazed grating is used to demodulate the changing spectrum that is got from the sensor system, and a line charge-coupled device (CCD) is used to accept the diffraction spectrum. Through analyzing the number of the CCD's pixels, we can get the amplitude of vibration and the change of the temperature. The experimental results show that the vibration amplitude of the exciter matches the detected signal under the stable frequency. The temperature shift and vibration signal are also successfully separated.

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Fiber Bragg grating (FBG) sensors have been a subject under continuous and rapid development since they were first demonstrated to be sensitive to strain and temperature[1]. They can measure many measurands such as strain (or force), displacement, temperature, vibration etc.. However, a FBG is sensitive to strain (or force, displacement) and temperature simultaneously, not respectively. In order to solve this problem, some papers[2−5] provide some approaches to distinguish the cross-sensitivity effect between strain and temperature. But corresponding sensors are not easy to be fabricated or need special technique. In this paper, we report a sensor that can measure vibration by using a FBG. Using a blazed grating and charge-coupled device (CCD) to analyze the signal makes our sensor have the capability of measuring the dynamic measurands in an easy way while not be disturbed by the temperature. The minimum vibration that can be detected is 0.01 mm in experiment.

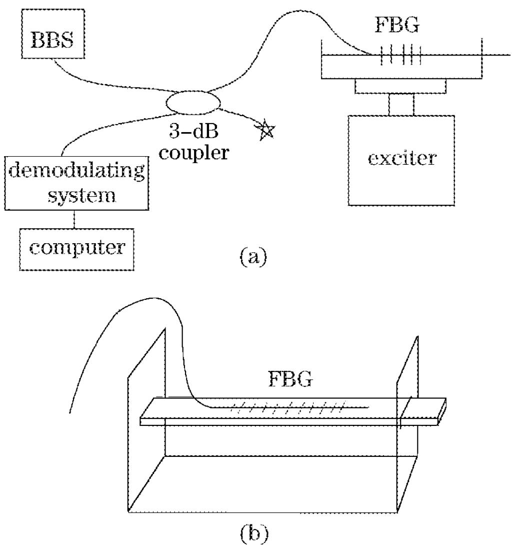

Fig. 1. The sketch map of the system. (a): The whole measuring system; (b): the structure of the detecting system. BBS: broadband source.

The sketch map of our system is shown in Fig. 1. It is made of a broadband source, a coupler, a FBG attached to a beam, a demodulating system, and a computer. The incident light from the broadband source is transmitted to the sensor system through the coupler (3 dB). A simple supported beam, which is fixed to a bracket with one end fixed and the other end free, forms the sensor with a FBG attached to its upper surface. The FBG is attached to the central location of the beam along the length so as to minimize the chirp effect when the beam bends (Fig. 1(b)).

The whole sensor system is fixed to the exciter, which can vibrate up and down in a fixed frequency. The upper layer of the simple supported beam lengthens when it bends to upper direction while shortens when it bends down. The beam's curvature changes when it vibrates, so the length of the FBG can be analyzed by curvature radius approximate theory. That is, when the curvature of the beam is μ, the length of the beam's upper layer can be expressed by

$$L = L_0(1 + h\mu/2), \tag{1}$$

where L_0 is the length of the beam's upper layer when μ is 0, h is the thickness of the beam. μ can be positive or negative, of which means bending to the different directions.

The simple supported beam resonates with the exciter when it vibrates. The resonant frequency of the simple supported beam is determined by the material, the length, and the shape of the section area. The simple supported beam can reflect the vibration of the exciter[6]. The wavelength of the FBG shifts when the beam vibrates. Supposing the length change of the FBG is equal to the length of the upper beam that it sticks to, the relationship between the reflected wavelength of the FBG and the change of the curvature μ is

$$\lambda_{\mathrm{B}} = \lambda_{\mathrm{B0}}(1 + (1 - p_{\mathrm{e}})h\mu/2), \tag{2}$$

where λ_{B0} is the reflected wavelength of the FBG when μ is 0, p_{e} is the effective optical-elastic index (~0.22).

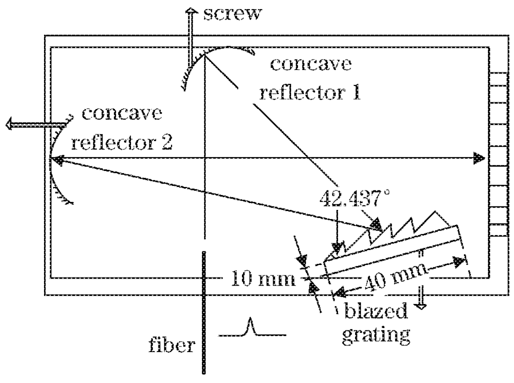

Fig. 2. The spectrum demodulating system.

From Eq. (2) we can see that λ_B is in linearity with the changing of μ as h is constant.

The spectrum demodulating system consists of two concave reflectors, a blazed grating, and a CCD (Fig. 2). The light route can be easily adjusted by adjusting the three screws in this system. Better optical efficiency can be achieved by a blazed grating designed such that the specular reflection (whose order corresponds to reflection of the individual blazed surfaces) of the incident light matches a particular interference order. In our experiment, we need the zeroth order of the individual blazed surface to matches the first interference order. Thus most of the spectrum's power is collected to the first interference order and greatly enlarges its intensity. According to grating equation we can get

$$2d\sin\theta_B = k\lambda_B, \tag{3}$$

where λ_B is blazed wavelength, k is the order of the spectrum, and θ_B is the blazed angle measured with respect to a plane parallel to the base of the grating. The central wavelength of FBG is 830 nm, the parameter of the blazed grating is 1200 line/mm. According to Eq. (3), we can get the blazed angle is 42.437°.

A very important thing is for certain number of FBG's wavelength shift, how many pixels we can get in the CCD. Through the dispersive power equation of the grating we can get

$$f = \frac{Dd\cos\theta_B}{k} = \frac{D\sqrt{d^2 - (d\sin\theta_B)^2}}{k} = \frac{D\sqrt{d^2 - (k\lambda)^2}}{k} = D\sqrt{d^2 - \lambda^2}, \tag{4}$$

where f is the focus of the concave reflector, D is the dispersive power of the blazed grating, d is the period of the grating, and k is 1.

Considering the fact that the light is very weak through the diffraction of the blazed grating, the foci of the two concave reflectors are all 100 mm. Thus the CCD can receive enough intensive signals. From Eq. (4) we can get D is 1.343 mm/nm. This indicates that for each 1-nm wavelength shift of the FBG, the shift of the spectrum received by CCD is 1.343 mm/nm. The size of each pixel is 13 μm. So each pixel represents 0.01-nm FBG's wavelength shift. In other words, for the FBG that the central wavelength is 830 nm, the minimum wavelength shift of FBG that CCD can detect is 0.01 nm.

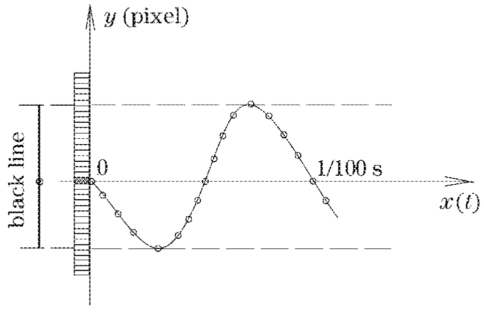

Fig. 3. The sinusoid formed by pixels.

Marking each pixel which receives the spectrum, we can get a sinusoid (Fig. 3). The amplitude of the sinusoid represents the amplitude of the vibration. As shown in Fig. 3, the x-axis represents time axis which crosses the midpoint and y-axis represents pixels. The dots in the sinusoid represent the pixels. All the pixels receive the spectrum form the black line. When the exciter keeps static, the FBG's reflecting spectrum forms a bright dot in the CCD that we define as origin. When the exciter vibrates, the spectrum reflects to different pixels. The pixels that receive the spectrum in one period can form a line through accumulation. The length of the black line is just the amplitude of the sinusoid. So different length of the black line represents different vibration amplitude. There is a corresponding relationship between the length of the line and the amplitude of the vibration. We can get the amplitude of the exciter's vibration through analyzing the length of the black line.

The shift of the temperature does not change the length of the black line (the amplitude of the sinusoid). It only makes the shift of the whole line or makes the shift of x-axis not the amplitude of the sinusoid. So the shift of x-axis represents the shift of the temperature and we can calculate it by analyzing the shift of the midpoint of the black line.

Different material, length, and shape of the section affect its resonant frequency. The material of the simple supported beam is plastic, and the size is 10 cm long, 0.4 cm wide, 0.3 cm thick. The wavelength of FBG is 830.07 nm, which is a little different from our previous hypothesis. This difference only affects the original site of central dot not the result of the experiment.

There are 612 pixels in the CCD. The static wavelength occupies 30 pixels of the CCD which represents the bandwidth of the FBG (0.30 nm). Vibration makes these pixels move up and down as a whole under these 30 pixels, which we mark it as the origin.

Figure 4 shows the relationship between the number of the points (the length that subtracts the origin from the black line) and the amplitude of the exciter's vibration under the temperature of 20 °C and frequency of 100 Hz.

From Fig. 4 we can see that the number of the pixels and the amplitude of the vibration are in linearity. This shows that our method is feasible. The minimum vibration amplitude of the exciter used in our experiment is

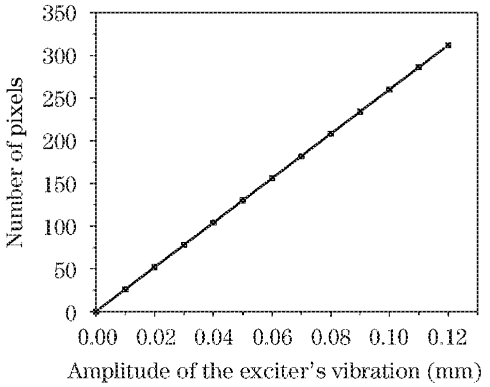

Fig. 4. The relationship between the number of pixels and the amplitude of the exciter's vibration.

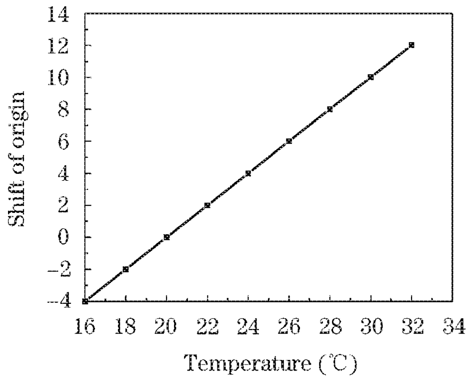

Fig. 5. The relationship between the temperature and the shift of the origin.

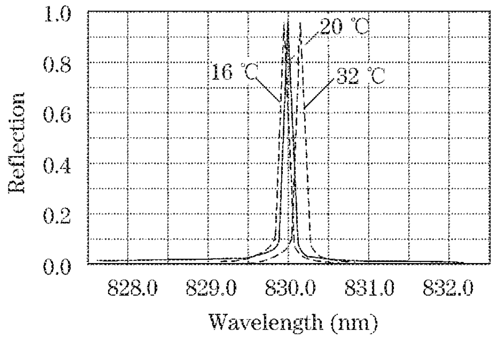

Fig. 6. The spectrum under different temperature.

0.01 mm. For each 0.01-mm change of the vibration, the change of the pixels is 26. Each pixel represents 0.4-μm vibration amplitude. This indicates that the sensor can measure the minimum vibration of 0.4 μm.

The relationship between the temperature change and the shift of the origin is show in Fig. 5. We can see that the central point shifts a pixel when the temperature shifts 1 °C. The wavelength of the FBG shifts 0.01 nm when the temperature changes 1 °C. Figure 6 shows the spectrum of the FBG under different temperature which is measured directly by spectrum analyzer. From 16 to 32 °C, the wavelength changes 0.18 nm, which is larger than we get from our sensor system. It is mainly because the edge of the spectrum is blurry and affects the CCD to count. Choosing a narrow bandwidth FBG can solve this problem. The FBG is stick to the supported beam, so larger pyrocondensatin of the supported beam can get a higher temperature precision.

In conclusion, this paper introduced a method of measuring the vibration by using a FBG and demodulating the spectrum with a blazed grating. The results show that the system can solve the FBG's cross sensitivity. This system is applicable to measuring the vibration of the generator's stator (100 Hz). The giant generator's safety is crucial to the power plant. But it tends to go wrong if working continuously, which may cause great disaster. Due to the strong magnetic field and high voltage inner generator, it is difficult to check the condition by using the traditional sensors. Therefore, our method is applicable to checking the generator simultaneously while it works and let us know the generator's working condition and take timely action if anything goes wrong.

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