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Analysis and Study of FBG Sensor in Crack Monitoring of Aircraft Structure

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Abstract. Based on the FBG sensing principle, the stress of each test point was measured by fatigue test with the change of tensile time using the strain sensitivity characteristics of FBG (fiber Bragg grating) sensor, and the experimental results were compared with the fatigue theory , FBG sensor can not only monitor the various stages of the crack growth, but also can effectively determine the time of occurrence of fatigue cracks and the top of the general location. This will provide a strong basis for the further application of FBG sensors in aircraft structural health monitoring.

Keywords: Fiber Bragg grating; Strain distribution; Crack monitoring; Fatigue theory; Aircraft structure.

1. Introduction

At present, the main structural materials of aircraft are metal materials, especially the bearing components of the structure are almost all made of aluminium alloy, strength steel and titanium alloy. Aluminum alloy has high corrosion resistance, good weldability and medium strength ratio, and is widely used in the manufacturing industries of aircraft, ships and automobiles. [5] Aluminum alloy accounts for more than 80% of the structural materials of the second generation fighter airframe designed and developed by our country, while the structural materials of the third generation fighter airframe still occupy 60%-70%.[5] During the service of the aircraft, the metal structure is subjected to alternating loads, and fatigue damage will inevitably occur. At the same time, there are many structural forms such as openings, slots and pins in the airframe structure, which are prone to fatigue cracks due to stress concentration. Crack initiation and propagation often cause sudden damage to aircraft structures, even serious accidents of aircraft destruction and human death. Therefore, it is necessary to monitor the integrity of aircraft metal structure in real time. Nowadays, acoustic emission (AE) is widely used to detect cracks in aeronautical structures, but the weight of the acoustic transmitter is heavy and the tangent interferes with each other, so there are few successful cases of structural damage detection. Because of its unique advantages such as light weight, fine diameter, small size and corrosion resistance, optical fiber sensing system has been widely valued by all walks of life and achieved rapid development.

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[1]Its application field covers a wide range, including structural health monitoring of aerospace, bridge and tunnel [5], power system, oil field industry, large-scale machinery and equipment, etc. [6] The research and application of aircraft structural health monitoring technology based on optical fiber sensing system has gradually become a new focus of attention of researchers in the field of Aeronautics and Astronautics at home and abroad. In this paper, FBG sensor is used to monitor the fatigue crack propagation process of aluminum alloy devices under the action of fatigue machine. First, the strain distribution of the structure and the position of sticking FBG sensor are obtained through finite element analysis; Then, the modem is used to demodulate the stress variation of FBG wavelength with time, and the crack propagation is monitored to verify the feasibility of the method.

2. Principle and Analysis of Fiber Bragg Grating Sensors

Principle of Fiber Bragg Grating Sensors. FBG sensing principle: When a wide-band incident light passes through the FBG, the incident light will be divided into two parts: reflected light and transmitted light. A part of the wavelength of the beam reflects when it is conditionally matched with the Bragg central wavelength, whereas the beam that cannot match the central wavelength transmits.

The central wavelength of the reflected beam is related to the FBG grating period and the effective refractive index of the fiber core, which satisfy the relationship:

$$\lambda_{\mathrm{B}} = 2n_{\mathrm{eff}}\Lambda \tag{1}$$

From Formula (1), we can draw the conclusion that both the direct influence, and any parameter change in either of them, will be reflected in the above. Therefore, when the change of any parameter in the external environmental factors leads to the change of FBG parameters or changes, it will also change. The total differential for formula (1) is:

$$\mathrm{d}\lambda_{\mathrm{B}} = 2n_{\mathrm{eff}}\mathrm{d}\Lambda + 2\Lambda\mathrm{d}n_{\mathrm{eff}} \tag{2}$$

The formula (2) can be rewritten as follows:

$$\Delta\lambda_{\mathrm{B}} = 2n_{\mathrm{eff}}\Delta\Lambda + 2\Lambda\Delta n_{\mathrm{eff}} \tag{3}$$

In the formula, Δn_{eff} , $\Delta\Lambda$ respectively represent the effective refractive index and the grating periodic variation.

Fiber Bragg grating strain sensing model. The force of FBG causes the fiber to stretch or shrink, which causes the value of the fiber parameters (Λ , n_{eff}) to change.

Assuming that FBG is only affected by axial stress during the detection process, and other factors are fixed, we establish a strain sensing model for FBG only under axial stress. Then, under the axial strain ε_x of size FBG, the expression of the grating period Λ is:

$$\Delta\Lambda = \varepsilon_x \Lambda \tag{4}$$

At the same time, the variation of the elastic light effect caused by the FBG material itself satisfies the expression:

$$\Delta n_{\mathrm{eff}} = -\frac{n_{\mathrm{eff}}^{3}[P_{12} - \nu(P_{11} + P_{12})]}{2}\varepsilon_x \tag{5}$$

It is obvious that the formula (6) is:

$$\frac{\Delta n_{\mathrm{eff}}}{n_{\mathrm{eff}}} = -\frac{n_{\mathrm{eff}}^{2}[P_{12} - \nu(P_{11} + P_{12})]}{2}\varepsilon_x \tag{6}$$

Formula: P_{ij} (j=1,2) is the coefficient of elasticity,ν is the Poisson's ratio.

The elastic light coefficient can be expressed as:

$$P_{\mathrm{e}} = \frac{n_{\mathrm{eff}}^{2}[P_{12} - \nu(P_{11} + P_{12})]}{2} \tag{7}$$

The formula (6) can also be written as follows:

$$\frac{\Delta n_{\text{eff}}}{n_{\text{eff}}} = -P_{\text{e}}\varepsilon_x \tag{8}$$

Substituting formula (8) into formula (3), there is:

$$\frac{\Delta\lambda_{\text{B}}}{\lambda_{\text{B}}} = (1-P_{\text{e}})\varepsilon_x \tag{9}$$

Sensitivity is:

$$K_{\varepsilon} = \Delta\lambda_{\text{B}} / \varepsilon_x \cdot \lambda_{\text{B}} = 1 - P_{\text{e}} \tag{10}$$

The elastic light coefficient of ordinary optical fiber is $P_{\text{e}} = 0.22$, formula(11) can be rewritten as follows:

$$\Delta\lambda_{\text{B}} = 0.78\varepsilon_x \cdot \lambda_{\text{B}} \tag{11}$$

According to formula (11), it can be found that once the change of central wavelength of FBG $\Delta\lambda_{\text{B}}$ is mastered, the magnitude of axial strain ε_x can be calculated.

3. Fatigue process and principle

Aluminum alloy fatigue has its own characteristics, and its whole fatigue process still conforms to the basic process of metal fatigue. The fatigue of metal components is a process of local damage caused by cyclic loads. The damage of materials under alternating loads accumulates slowly, which makes permanent changes in the local structure of materials. After a certain number of cycles, cracks initiate and expand, and finally break [8]. During cyclic loading, it is easy for members to undergo local plastic deformation in the highest stress region, which results in permanent damage and crack propagation of materials. With the increase of cyclic loading times, the crack length (damage) also increases. After the crack reaches the critical value, the part will fail (fracture).

In the existing fatigue theory research, the fatigue process is generally divided into four stages[9]: (1) crack nucleation; (2) microcrack propagation; (3) macro-crack propagation; (4) final fracture. Crack nucleation is the first step in fatigue process. Cracks are easy to initiate on local shear planes near high stress concentration, such as stable slip bands, inclusions and looseness. Once cracks nucleate and continue to apply cyclic loads, cracks will propagate along the maximum shear stress plane through grain boundaries.

4. Experimental specimen and fiber Bragg grating distribution

The experimental specimen is shown in Figure 1. The material is aluminum alloy widely used in the aircraft manufacturing industry. The basic size is 140 mm x 80 mm x 2 mm. A crack with a length of 20 mm and a width of 0.2 mm was prefabricated in the middle of the specimen. The purpose is to produce obvious crack expansion phenomenon and shorten the fatigue test time.

Figure 1. Aluminum alloy experimental specimen

In order to accurately monitor the stress change of the experimental specimens during crack propagation, the number and location of FBG pastes were optimized by using finite element analysis software. As shown in Figure 2, 13 FBGs were pasted in the vertical direction of cracks in the experimental specimens, with 5 mm longitudinal interval between two adjacent FBGs. No. 1-13 of FBG was divided from bottom to top. The grating No. 7 is placed in the middle of the board. The other gratings are symmetrically distributed. The central wavelength of each grating is shown in Figure 2.

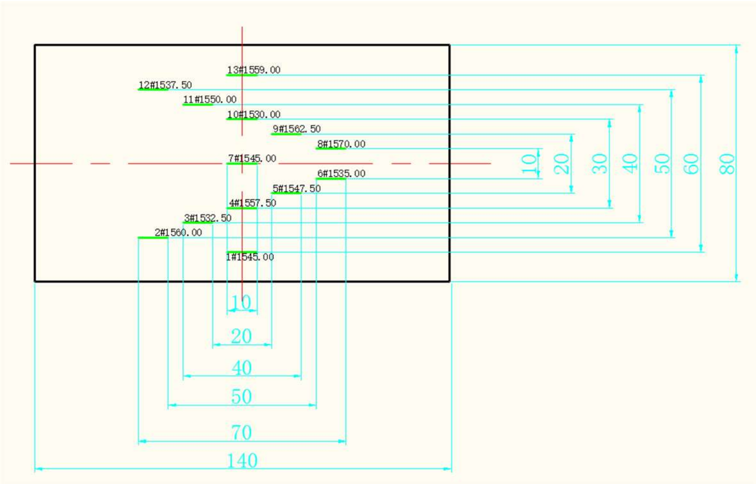

Figure 2. Fiber grating sticky map

5. Experiment

Experimental system and method. The test system is mainly composed of LandMark-250 fatigue testing machine, FBG demodulation module, computer, FBG, annulus, light source and test specimens as shown in Figure 3. As shown in Fig. 4, the FBG-bonded experimental specimens are clamped on the fatigue testing machine, which imposes a load of 3KN-56KN on the specimens with a frequency of 10Hz. FBG demodulation module is used to collect data. The acquisition frequency of the demodulation module is 100Hz.

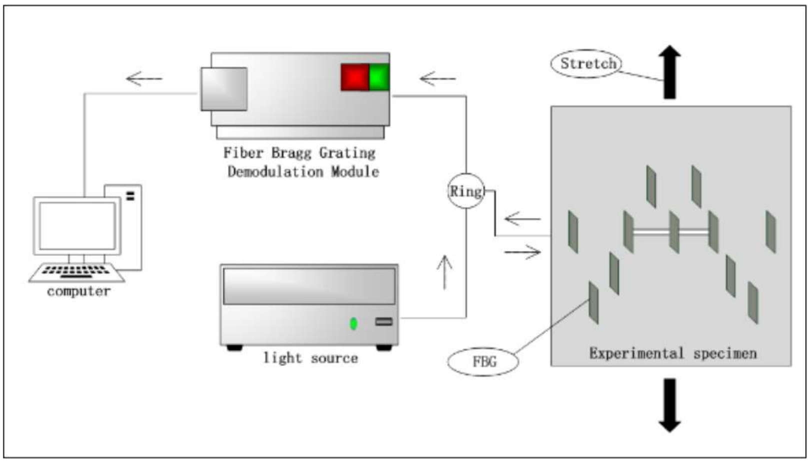

Figure 3. Schematic diagram of experimental system

Figure 4. Comparison of fatigue testing machine before and after stretching

Experimental results and analysis. Fig5 is a graph showing the stress of the corresponding FBG monitoring points with the tensile time of the experimental specimens. It can be seen that the stress does not change after the cyclic load is applied for 30 s, and the test piece is broken. Under the cyclic load, the stress of the monitoring points from 1 to 13 changes with time, among which 1 and 13, 2 and 12, 3 and 11, 4 and 10, 5 and after the cyclic load is applied to the monitoring points No. 9, No. 6, and No. 8, the stress changes are basically the same, which indicates that the cracks are uniformly spread up and down after the experimental specimen is stretched. Therefore, only the test No. 1-7 is given in the following figure. Among them, No. 1, No. 4, No. 7 are on the crack or on the extension line. In the initial stage, the wavelength variables are 3.8 nm, 4.8 nm and 7.3 nm respectively, and the wavelength variable shows an increasing trend with the progress of time; At the 12th second, the 7th grating wavelength variable began to increase, and the 21st grating wavelength variable began to increase until the 21st second, until the 27th second grating wavelength began to increase; and 2, 3, 5, and 6, the grating wavelength variable does not increase significantly indicating that the crack propagation is along the pre-crack, and as the fatigue drawing process progresses, the crack length increases. The No. 2 grating wavelength variable did not change significantly during the fatigue test, which indicates that the crack propagation has no significant effect on the strain at the No. 2 grating position.

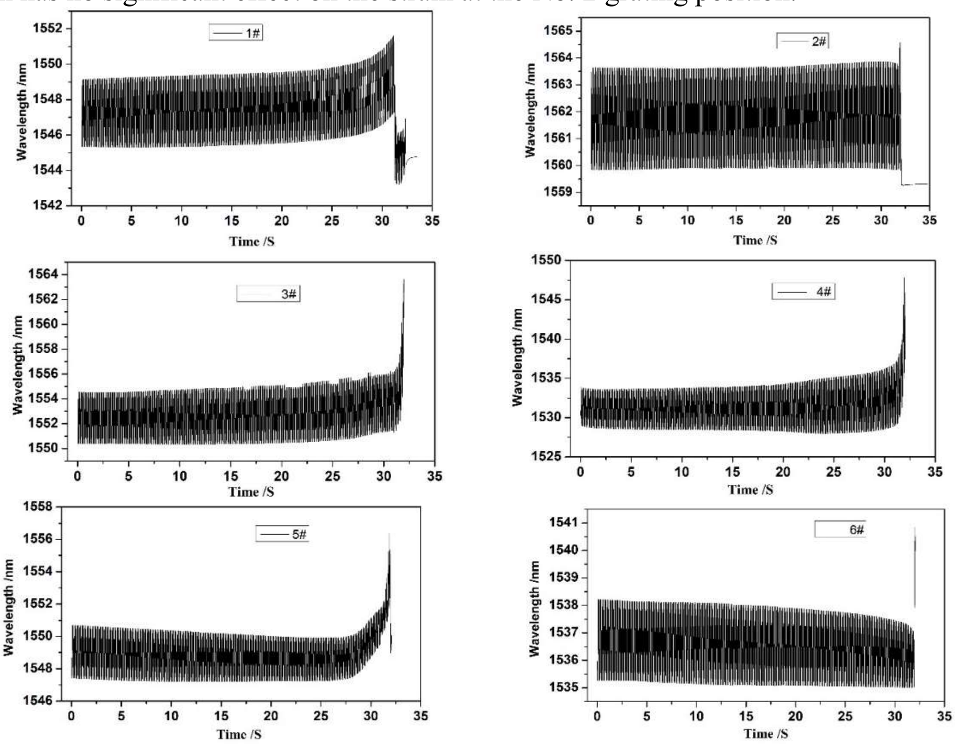

Figure 5. Corresponding FBG monitoring points stress change with drawing time

Fig. 6 illustrates in detail the various stages of monitoring signal at monitoring point 7 (vertical prefabricated crack) of the experimental specimen. It can be seen that the general change trend of stress in the fatigue process of aluminium alloy can well correspond to each stage of the fatigue process. Because of the pre-fabricated cracks, the cracks in the initial stage have nucleated, so they are under cyclic loading. In the initial stage, the stress changes are not obvious; then for a long period of time, the stress has been periodically weak fluctuation, there is no significant change which can be seen as crack growth; in the final stage of monitoring, the stress increases sharply, reaching the maximum. Then the sample instantaneous fracture, and the entire monitoring process is over.

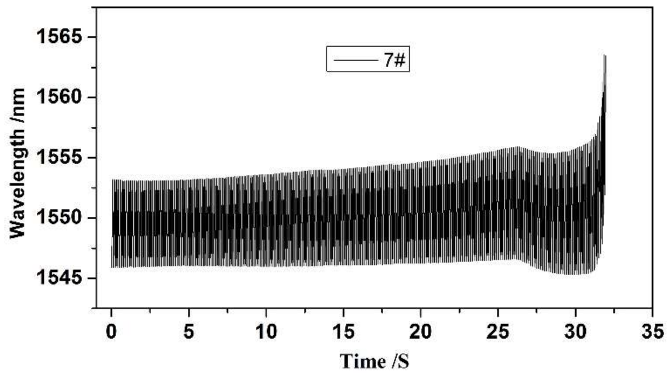

Figure 6. Change of stress on the 7th FBG monitoring point with stretching time

The experimental results show that the method of monitoring crack growth with FBG sensor is feasible, and to some extent, it can reflect the time of crack occurrence and the location of crack tip.

6. Conclusion

The fatigue crack growth of aluminum alloy specimens with precast cracks was studied by FBG sensor. According to the strain field distribution obtained by the finite element model, the paste position of the FBG sensor is determined. By comparing the changes of stress at each monitoring point with time, it is found that the FBG sensor can not only monitor the crack propagation, but also effectively determine the time when the fatigue crack occurs and the approximate location of its top. The results provide a strong basis for the further application of FBG sensors in aircraft structural health monitoring. In addition, according to the corresponding relationship between wavelength and stress, a safety early warning system can be designed. A range of safety early warning wavelength is preset in the system. When crack propagation exceeds this range, automatic alarm can be given.

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