Reliability Analysis of Fiber Bragg Grating Sensors packaged with Carbon Fiber Reinforced Plastics based on FMEA

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Abstract: The performance of packaged Fiber Bragg grating (FBG) sensors with carbon fiber reinforced plastic (CFRP) may degrade even functional failure with the working time increases. The reliability of this kind of packaged FBG sensors has been analyzed by using the FMEA method in this paper. Considering the working environment of FBG sensor, such as alternating loads and ageing, the related failure modes are discussed. The risk index of each failure mode is calculated. The relationship between different failure modes is analyzed, and as well as the weak links of the packaging design and process of the FBG sensor. The results are helpful to improve the availability and the reliability of packaged FBG sensor by CFRP.

1. Introduction

Wind-generated electricity is the most rapidly developing renewable energy technology in recent years. It has received enormous attention all over the world for its advantages such as low pollution, large storage, wide range, etc. Wind turbine blade (WTB) is one of the core components of wind turbines, and it is also easy to fail. Thus, the availability and reliability of the WTB is important to the safety of the whole wind turbine. Full-scale structural test of rotor blade test is an important method to verify the validity of blade design and manufacturing rationality, and it is also an effective way to ensure the reliability and stability of the WTBs. FBG sensors are used in the structural tests of the WTBs for their advantages such as light weight, networking, anti-electromagnetic interference, anti-corrosion, etc. However, FBG sensors are brittle and fragile, so they must be packaged before used. As we known, the WTBs are generally made of composite materials, thus CFRP are used to package FBG sensors for their high strength, high modulus, high temperature resistance, and the more importantly, good compatibility with composite materials[1].

Under the combined influences of working environment, alternating load and other factors in practical engineering application, FBG sensors often have performance degradation and function failures along with the working time increases[2]. Wen[3] studied the sensing characteristics of metallized FBG under high temperature conditions through short time high temperature failure test, and found that FBG sensor has obvious attenuation of temperature sensitivity, spectral characteristics and power, which verifies that there is degradation of spectral and reflection peak power in FBG sensor during operation. Liu[4] studied the fatigue characteristics of adhesive-packaged FBG sensor by strain response test, and the results show that the sensitivity, repeatability and consistency of the sensor decrease after a period of vibration. Zhang[5] studied the strain transfer characteristics of the
FBG sensor by considering the effect of transverse stress, analyzed the effect of the bonding layer on the average strain transfer efficiency of the FBG sensor, and verified that the deterioration of the bonding layer caused the degradation of the strain transfer ratio of the FBG sensor. Thus, the quality and performance of FBG sensors are not stable in the application process, so it is very important to analyze the reliability of FBG sensors.

In this paper, the reliability analysis of FBG sensor packaged with CFRP is carried out. Firstly, the FMEA principle is given in section 2. In section 3, the detailed structure of FBG sensor packaged with CFRP is introduced, then the FMEA of the whole object is studied. Finally, it gives the conclusion.

2. Introduction to FMEA method
Failure mode and effect analysis (FMEA) is one of the important methods for reliability analysis and preventive design of products. It aims to find out the direct and potential defects in product design, process design, equipment design and other stages, then analyze the failure modes of each component and the failure impact on the upper hierarchy structure. Through the analysis of all possible failure modes, causes and effects of failures in the system, the corresponding improvement methods and failure prevention measures are put forward, so as to improve the availability and reliability of products.

FMEA analysis method is a bottom-up analysis program and it is the basis of fault tree analysis (FTA). The analysis flow is shown in Fig. 1.

3. FMEA analysis of FBG sensors packaged with CFRP
3.1. Structure of FBG sensors packaged with CFRP
Fiber Bragg grating (FBG) sensor is a kind of sensor whose core refractive index changes periodically along the axis of the fiber. When light from the broadband light source enters the grating, the light meeting the wavelength of FBG in the spectrum will be reflected, and other wavelengths will continue to transmit through the FBG. The structure of FBG is shown in Fig. 2.

The basic expression of reflection wavelength of fiber Bragg grating is as follows:

\[ \lambda_B = 2n_{\text{eff}}\Lambda \]

where \( \lambda_B \) is the reflection center wavelength of the fiber grating, \( n_{\text{eff}} \) is the grating period, and \( \Lambda \) is the effective refractive index of the reverse coupled mode.
The FBG sensor packaged with CFRP is mainly composed of three parts: Fiber Bragg grating (FBG), packaging layer (CFRP) and bond layer. The FBG sensors are protected by the packaging layer and glued on the blade surface by the bond layer after packaged. The structure is shown in Fig. 3.

![Fig. 3 The Structure of FBG sensor packaged with CFRP](image)

### 3.2. FMEA analysis of FBG sensors packaged with CFRP

In the full-scale structural test of rotor blade testing, the FBG sensors packaged with CFRP are pasted on the blade surface. Due to the particular testing environment of the blade, the performance and reliability of the FBG sensors will be affected and degenerated. By studying the faults may occur and the fault data of FBG sensors in similar systems, the fault mode, fault causes and fault effects of FBG sensor packaged with CFRP are analyzed, and the FMEA table of FBG sensor packaged with CFRP is output. According to the engineering experience and expert opinions, the severity(S), occurrence(O) and detection(D) of different fault modes are analyzed, and the RPNs of different failure modes are calculated. The FMEA table of FBG sensor packaged with CFRP is shown in Tab. 1.

| No. | Functional module | Failure mode | Cause of failure | Fault effects | S  | O  | D  | RPN |
|-----|-------------------|--------------|-----------------|---------------|----|----|----|-----|
| 1   | FBG sensor        | Gate break   | Extensive construction | FBG sensor cannot be used | 8  | 2  | 3  | 48  |
| 2   | FBG sensor        | Sidelobe interference | Excessive welding loss | FBG sensor detected multiple peaks | 8  | 3  | 4  | 96  |
| 3   | FBG sensor        | No output    | The turning radius of leading out tail gate is too small | FBG sensor cannot be used | 9  | 1  | 4  | 36  |
| 4   | FBG sensor        | Misinformation | Unstable supply voltage | Inaccurate FBG sensor measurement | 6  | 4  | 3  | 72  |
| 5   | FBG sensor        | Signal drift | External environment interference | FBG sensor cannot be used | 8  | 4  | 3  | 96  |
| 6   | FBG sensor        | Signal discontinuity | External environment interference | FBG sensor cannot be used | 8  | 3  | 3  | 72  |
| 7   | FBG sensor        | The strain transfer rate decreases | The bonding parameters and package parameters changed | Inaccurate FBG sensor measurement | 6  | 4  | 5  | 120 |
| 8   | Packaging layer of CFRP | Layered | Material under impact | The compressive strength and buckling load of the sensor decrease | 6  | 4  | 4  | 96  |
| 9   | Packaging layer of CFRP | Dehiscence | Single direction laying of carbon fiber | The accuracy of strain measurement is reduced and the service life is reduced | 6  | 2  | 3  | 36  |
| 10  | Warping           | Excessive temperature and pressure during packaging | Material deformation and fiber bending | | 6  | 3  | 4  | 72  |
According to Tab.1, the FBG sensor have a variety of failure modes under the coupling influence of long-term alternating load and harsh environment. The CFRP fracture may cause the damage of the packaging layer, the invasion of impurities, and even the fracture of the optical fiber, which lead the sensor damaged and fail to monitor. Due to improper process operation and mismatching of structural parameters, power loss will occur in optical fiber connection, resulting in the decrease of sensor transmission distance, abnormal data transmission and the decrease of accuracy of strain measurement results. Fiber Bragg grating demodulator may be failed for the quality defects and human error operation. The RPN values of different failure modes can be obtained by evaluating the severity, occurrence and detection of different failure modes, as shown in Fig. 4.
From Fig. 4, it can be seen that the failure modes with highest risk are the decrease of strain transfer rate caused by the parameters change of packaging layer and bonding layer, the inappropriate curing temperature of bond, the cracking of bonding layer caused by section stress concentration, and the power loss of connecting components caused by improper operation of optical fiber connection process and mismatch of structural parameters. The above failure modes will make the FBG sensor fail to complete the monitoring work, and further affect the fatigue life prediction and health state assessment of the wind turbine blades.

4. Conclusions
FMEA method is used to analyze the reliability of a kind of FBG sensors packaged with CFRP. Some conclusions are as followings:

(1) The performance failures of packaged FBG sensor are mainly manifested as the decline of its strain transmission rate and the bond strength, and the power loss.

(2) The material and packaging technology used to fabricate the sensor are crucial to the reliability of the packaged FBG sensor. It should be taken seriously, especially when FBG sensors are used for long-term structural health monitoring of actual WTB.

(3) It is effective and beneficial that the manufacturer takes detailed fault statistics, the fault maintenance measures, and strictly evaluates the equipment according to the relevant standards and specifications.

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